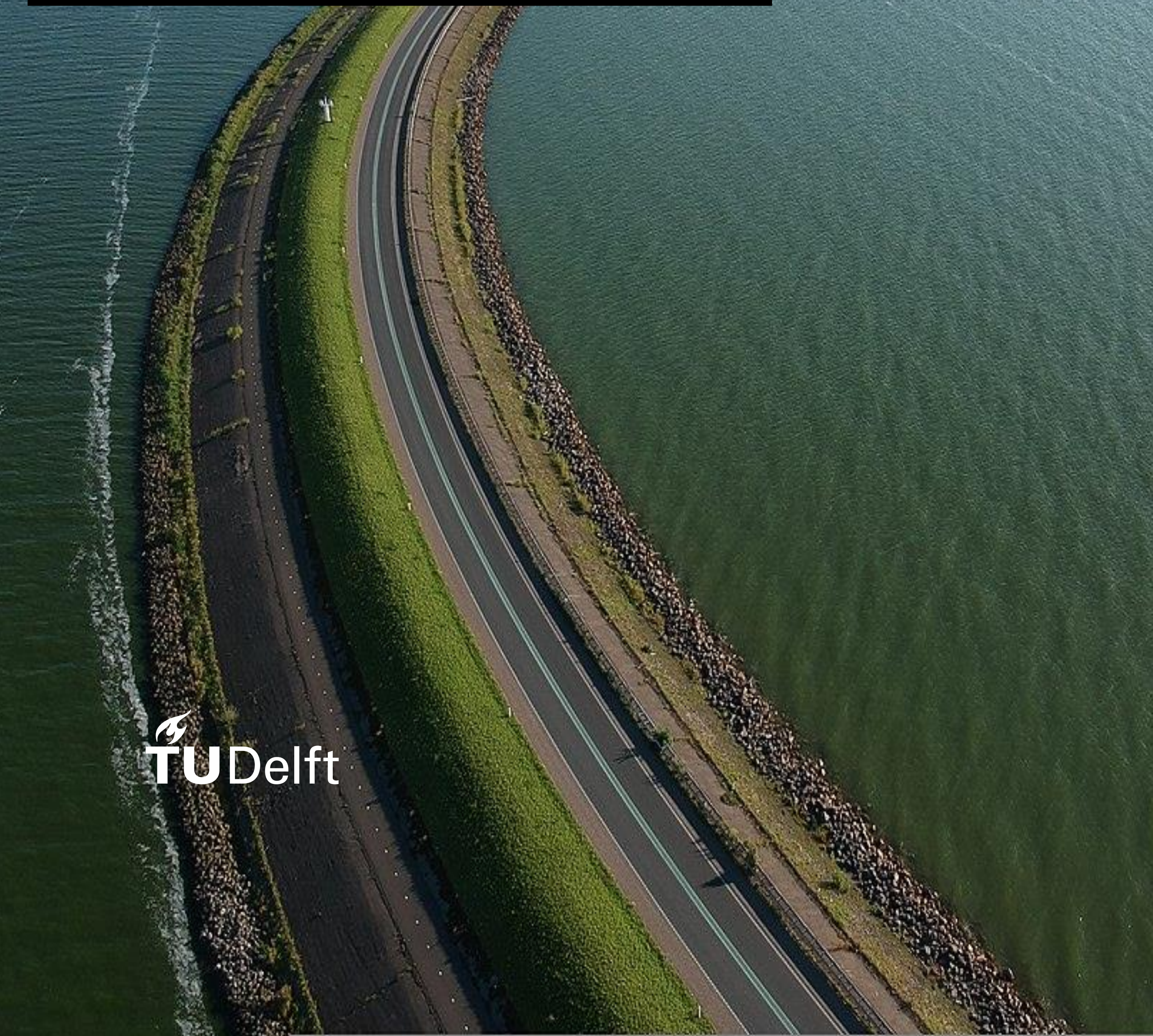
Translating Management Maturity Levels to Flood Defences Asset Cost and Performance using Dynamic Bayesian Networks

Radityo Andjaringrat Adhi



TU Delft

Translating Management Maturity Levels to Flood Defences Asset Cost and Performance using Dynamic Bayesian Networks

Additional Thesis

By

Radityo Andjaringrat Adhi

Master of Science

in Hydraulic Engineering

Main Supervisor:	Wouter Jan Klerk (TU Delft/Deltares)
Thesis committee:	Prof. Matthijs Kok (TU Delft)
	Ir. Martine van den Boomen (TU Delft)

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

Preface

As a part of the Hydraulic Engineering Master Program and in order to gain practical knowledge in the field of Hydraulic Engineering, I am required to do an additional thesis. The topic that was chosen is based on the writer interest on Flood Risk Management. The primary objective behind doing this thesis is to get knowledge and experience on a different approach of flood risk management.

In this mini-thesis, I have considered various practical problems, concepts, effects and implications regarding the maturity model of asset management. This project has helped me to broaden my perspective and knowledge regarding the management surround hydraulic structures and probabilistic methods. Through this experience, I come to acknowledge that the scope of flood risk management is broad and there is still improvement that needed to be done.

Radityo Andjaringrat Adhi

Delft, November 2018

Table of Contents

Abstract

Maturity model is widely known as an assessment tool to understand an organization management capabilities and identifying potential improvement. The model demonstrates informative results towards the organization management maturity but hard to acknowledge the influence of potential improvement towards the organization's asset performance. There have not yet been a study on measuring the asset performance conditional of the organization management maturity. This research objective is to develop an approach to translates maturity model to an asset lifecycle cost and performance by using Dynamic Bayesian Network (DBN). This research uses semi-hypothetical case to see how the model might unfold and to learn the possibility of maturity model development. The chosen hypothetical case is the organizational decision-making process of grass revetment maintenance during winter season based on information management maturity. The output of the DBN is the expected annual cost of the asset for a grass revetment maintenance conditional to organization information management maturity. The result is analyzed by using Value of Information (VOI) which enables us to understand the influence of information management maturity towards the asset lifecycle cost. This research has led us to the conclusion that it is feasible to associate asset lifecycle cost and performance with the organization information management maturity by translating the case into a DBN. In general, this research can potentially lead to a better application on the maturity model and might be used for the organization decision process. This study is the first step towards enhancing our understanding of maturity model application and its implication towards the asset performance.

Acknowledgments

I would like to express my special thanks to my supervisor Wouter Jan Klerk and Prof. Matthijs Kok, who gave me a golden opportunity to do this wonderful FAIR Project with Deltares who also helped me in completing this project. I want to thank also for everyone, Mr. Berry, Mrs. Karolina, and Mr. Frank de Heijer that has helped me throughout this project. I came to know about so many new knowledge and experience. Secondly, I would like to thank my parents and friends who gave me support. Third, I would like to thank Indonesia Endowment Fund for Education who helped me financially and the opportunity to study in TU Delft.

Radityo Andjaringrat Adhi

Master Candidate of Hydraulic Engineering

1 Introduction

1.1 Background

1.1.1. Flood Defences Infrastructure and Development

The number of population which are settled in flood-prone areas are growing and expected to grow (Arnell et al., 2016). Due to the danger of economic damages, societal loss and casualties, flood defenses infrastructures become an essential structure for flood-prone areas (S.N. Jonkman et al., 2017). Despite flood defenses structures are commonly applied, the risk of flood disasters is increasing for many flood-prone areas owing to global and regional changes in climate conditions and sea level (Temmerman et al., 2013). Based on recent research in the IPCC report, the sea level rise may increase until three meters in 2100 which is caused by global warming (Le Bars et al., 2017)

Human settlements in coastal lowlands are vulnerable to risk resulting from climate change, yet these lowlands are rapidly growing (McGranahan et al., 2007). Flood protection is major importance which requires substantial investment and maintenance cost (Postek et al., 2018). A permanent and absolute protection structure is nearly and most likely impossible to build, due to high cost and inherent uncertainties (Schanze et al., 2011). The common practice for flood defenses is to build and maintain the structure performance at a required level.

Risk management has been receiving high attention within the flood research which shifts the regional policies from flood protection to flood risk management (Schanze et al., 2011). Flood risk management aims to reduce the economic and societal consequences from a flood hazard threat (Commission of the European Communities, 2004). A flood risk management program incorporates prevention measures, mitigation measures, protection measures, emergency measures, and recovery. If a flood defenses structure is present, adaptation investments are generally implemented during the process of structure lifetime to provide reliability (Hallegatte et al., 2013). Mitigation measures are also aimed to reduce the potential consequences of the flood (Kind, 2014).

1.1.2. Lifecycle Asset Management

Asset management is a common and important field of study in flood risk management paradigm (Vlad, 2017). Infrastructure owners are facing in an increasingly challenging economic, political, and climate setting. Asset owners are seeking a novel approach to attain a higher value, for a less overall cost, from their assets (Parlikad et al., 2016). An efficient lifecycle asset management requires a holistic approach to asset development and preservation that ensures maximum service performance at minimum lifecycle cost (Giglio et al., 2018).

Furthermore, in flood risk management practice, organizations still face uncertainties concerning asset delivery (Thorne et al., 2018). A higher uncertainty of asset delivery can cause an inefficiency towards asset performance. A poor asset management is caused by an ineffective decision. Lack of asset management focus can lead to problems from poor communication between operations and maintenance that may lead to a higher failure asset risk (Hastings, 2014). An organization asset management performance can be evaluated by using maturity models (Mettler, 2011).

1.1.3. Maturity Model

Maturity model is a tool to measure or evaluate organization management maturity. It is often used as a communication tool for organization evaluation. Asset management maturity is the extent to which capabilities, performance and ongoing assurance of an organization are fit for purpose to meet the current and future needs of its stakeholders, including the organization ability to respond and foresee to its operating asset (GFMAM, 2015). In other words, a mature organization is most likely to fulfill its current or future needs and has a well-maintained functioning asset. Asset management supports the realization of value while balancing financial, environmental and social cost, risk level and quality service of asset performance (Hastings, 2014).

Maturity model has been developed and produces several models. Each maturity models have a different approach to measuring organization management maturity. For this research, only Infrastructure Management Maturity Matrix is applied. There are five maturity levels according to the Infrastructure Management Maturity Matrix (IM3) which distinct the efficiency of management towards the asset at each level(Volker et al., 2013). The IM3 model provides a structure for measuring the maturity level of asset management within the organization by using seven dimension or indicators. Management dimension is the focal points of an implementation strategy for asset management. These seven indicators can describe aspects of asset management, such as asset management decision making, leadership, information management, and so forth.

Rijkswaterstaat applied maturity model in 2008 to assess their asset management maturity, and it has shown a significant improvement in several aspects (Volker et al., 2013). Maturity model is proven to be a useful insight to the organization in their management evaluation based on Volker research. However, this model assessment can only obtain asset management maturity. The output of the model is informative but has room for improvement. Since the output is used as information in a decision process, one of the model improvements is to translate the maturity level of an organization maturity into a project indicator such as cost and performance.

The improvement as mentioned above notion may help an organization decision-making process on whether to improve their management maturity. The model improvement or extension will involve asset cost and performance through the maturity model. The organization expenditure towards an asset exists through a decision process. Therefore, the approach of quantifying organization expenditure towards an asset based on maturity levels will involve decision probability. The existence of decision probability leads us to a premise that by using Dynamic Bayesian Network, it is possible to calculate the expected cost of an asset through decision network. Dynamic Bayesian Network (DBN) is a Bayesian network which relates variables over adjacent time-steps. By using this method, it enables us to recreate an organization decision process towards an asset by considering the decision probability at each process.

1.1.4. FAIR Project

All North Sea Region (NSR) countries aim to improve the maintenance of existing flood defenses infrastructure to overcome the uncertainty of flood events in the future and the uncertainty of infrastructure performance deterioration. The FAIR project (Flood defense infrastructure Asset management & Investment in Renovation Adaptation, Optimisation, and Maintenance) has an objective to reduce flood risk in the NSR by demonstrating climate change adaptation solutions to improve the performance of flood infrastructure with a cost-effective investment (European Regional Development Fund, 2015). This project involves six different countries which have a dependency towards the North Sea namely: Belgium, Germany, Denmark, Sweden, Norway, and The Netherlands. As part of the FAIR project, this research is intended to develop and contribute to the development of an optimal decision process. The model in this research is developed based the relevance and the applicability towards countries involved in the FAIR project.

1.2 Problem Statement

The result of the maturity model does explain the organization management performance to a small extent. Unfortunately, the model results merely indicate the organization growth which has the potential to be a learning curve amongst the organization (Volker et al., 2013). However, the maturity model has the potential to be improved by relating to the organization maturity significance towards asset lifecycle cost and performance. The translation of maturity model towards annual asset cost is not yet known and would be useful as information for organization management assessment. The result of the maturity model translation would be beneficial for the organization in the decision-making process of maturity improvement.

One of the challenges of the maturity model development is to study the interrelation between management dimensions. Within the seven dimensions, it can be perceived that they are connected, mainly through shared practices (Volker et al., 2011). For this research, only information management is considered and modeled to outset the model development. Information management is the data and information held within the organization's asset information system and the processes for the management and governance of that data and information (IAM, 2012). Information management can be defined as the accessibility and quality of knowledge attained by the organization's asset. Information is an essential aspect of decision-making, especially during an asset lifecycle management.

In a nutshell, maturity model is an essential tool to acknowledge the organization growth of their management capability. Previous work has only focused on the maturity model implementation on the learning growth of an organization. We believe that the maturity model can be extended to acquire further information on the repercussion of organization maturity towards asset cost and performance throughout its lifecycle cost and performance. This research aims to translate information management maturity levels to asset lifecycle cost and performance by using Dynamic Bayesian network on a hypothetical case. The hypothetical case is chosen to be relatable to the NSR countries in the FAIR project. The result of this research can be the initial to future research concerning maturity level translation and may contribute to the FAIR Project concerning asset management improvement.

1.3 Objectives

The objective of this research is to translate information management maturity level into asset lifecycle cost and performance by using a Dynamic Bayesian Network

1.4 Research Questions

The research question is meant to answer the gap knowledge stated in the problem statement. The research question will be:

How to translate information management maturity levels to asset lifecycle cost and performance specifically for flood defenses?

In order to support the primary research question, sub-research questions are formulated as follows:

- How does the organization information management maturity translate to a flood defense's management activity case study?
  Information management is an asset management dimension based on IM^3 which describes the organization capability on managing information. The relation of information management maturity and a specific flood defense's management activity is unclear. In order to relate between the maturity and management's activity, an additional term is made as an approach which later is described as a 'capability analysis' (see 3.2.3 Management Dimensions and Activity Translation)
- How can the asset cost and performance be measured through maturity levels in the case study?
  Asset lifecycle cost and performance are reliant on the organization decision-making quality. In order to obtain the asset cost and performance in different maturity, the semi-hypothetical case is developed by using Dynamic Bayesian Network. The method is

chosen due to the probabilistic existence in the organization decision process. This method is believed to be appropriate to measure asset cost and performance.

1.5 Research Report Framework

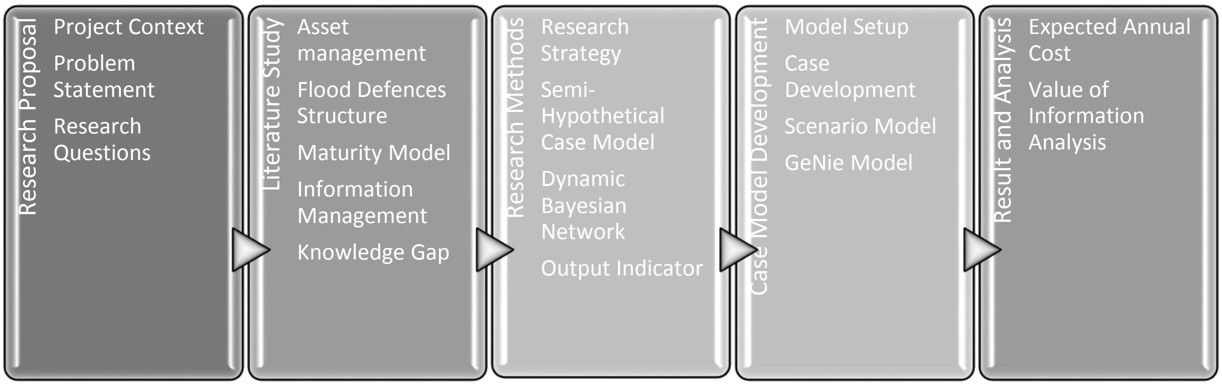


Figure 1 Report framework

The graph in Figure 1 explains the process of this research. First the project context, problem statement and research question are developed. The research questions determine the research approach. Second, literature studies are used to gather information on maturity levels and information management. This stage will result in the development of a quantitative information management maturity model and to know the knowledge gap of this research topic. In the third stage, the methodology of the model development is explained. At the fourth stage, the case model is developed using the DBN on the semi-hypothetical case. At a later stage, the constructed model is chosen as a conclusion with a recommendation for future research surrounding this problem.

2 Literature Review

This chapter discusses the fundamental understanding of some essential aspects of this research. The fundamental aspect of this research involves asset management, flood defenses management, maturity model, and information management. This chapter also discusses the knowledge gaps found in the aforementioned aspects.

2.1 Asset Management

An asset is a thing or entity that has a potential value to an organization (IAM, 2012). There are several types of assets identified within the organization, such as physical assets, financial assets, human assets, information assets, and intangible assets. In order to maintain an asset value, the organization performs activities that preserve the functional and business value to the organization or usually called asset management (Hastings, 2014). Asset management is relevant whether they are large, small, private, public, government, or not for profit, which focuses on delivering a specific value and achieve the organization's business objective.

The increasing complexity of infrastructure management ensued in a comprehensive and diverse area of expertise, knowledge, and responsibility (Halfawy, 2008). As results, challenges arise to improve the efficiency of managing assets through implementing efficient, sustainable, and proactive asset management strategies. There is growing evidence that effective asset management can improve an organization reputation and its ability to acquire a good asset performance (IAM, 2012). Asset management can ensure that the asset operates safely, produces the expected performance, and helps in evaluating and reducing the cost of managing assets.

Most of assets have a lifetime of functional operations. There are several activities to support asset lifetimes, such as maintenance strategies, component replacement, asset replacement, recycling and other option to manage assets. In order achieve an optimal investment towards asset, it is necessary to apply life cycle costing and value optimization techniques which will support the asset decision in relation with cost, risk and value opportunities for a short or long term impact intervention (IAM, 2012). Therefore, strategies and organization decision making quality is crucial for asset performance.

2.2 Flood defenses management

A flood defense is a hydraulic structure which has a function to protect against flooding against the flood-prone area (S.N. Jonkman et al., 2017). A flood defense can be considered as an asset to the entity that has dependency over its function which is the government, private sector, and other stakeholders. Flood defenses have a different type of structure for a different condition which contains different essential components for example revetments in a river dike, weir, and spillway in a dam. (Tourment et al., 2017).

Extreme climatic events coupled with other inherent causal have led to the deterioration of the flood control structure along the river (Lazanyi et al., 1997). It is inevitable that flood defense performance can degrade in time due to external forces and deterioration of their components. The asset manager has the authority to intervene and control the future of the structure. Decisions regarding the maintenance of structures are usually made on the basis of expected costs (Kuijper et al., 2012). An efficient investment for optimal maintenance is a priority to keep the asset lifecycle value as optimized as possible (Buijs et al., 2009).

In general, maintenance is executed when the asset performance is predicted below than expected or below the required level of protection. In flood defenses, the level of protection is specified by law and may vary along the location and condition (Kind, 2014). Due to the rising of climate events and the population growth in certain areas, reinforcement projects are complex and resulting high reinforcement cost (Sebastiaan N. Jonkman et al., 2018). Hence, the focus of management is not only to provide the required reinforcement, but also the efficient management of structures to achieve a tight budget. The management performance can be measured by using a maturity model.

2.3 Maturity Model

There is a considerable amount of literature on maturity models applied to an organization's asset such as coal-mining industry (Foster et al., 2013), public infrastructure (Volker et al., 2013), and energy (Introna et al., 2014). In the beginning, Maturity level or Capability Maturity Model was early developed to measure and assessing the ability of government contractors' processes to implement contracted software. The model was first applied in IEEE Software

(Humphrey, 1987). As the concept has developed, the maturity model is extended to measure the organization management maturity towards an asset.

Maturity describes evolutionary progress in the exhibition of a specific ability or the accomplishment of a target from an initial condition to a normally end-stage (Mettler, 2011). A maturity model is an approach to assess the organization's performances in managing its business and develop to better management. Practitioners and academics have developed several maturity assessment models such as such as IM^3 (Infrastructure management maturity matrix), SCEMM Supply Chain Excellence Maturity Model), MSU (Purchasing Excellence Publiek Model), IMT (Infra Maturity Tool and Project). There are five levels based known (Williams et al., 2003) which are:

Table 1 Matrix of maturity levels

Ad-Hoc	The organization has limited experience and does not have learning documents to repeat their decision/performance.
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 processes. 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 experience to change the way it operates.

Despite the variety maturity model available, this research focuses solely on Infrastructure management maturity matrix (IM^3) which recently has been applied by Rijkswaterstaat. A maturity model is generally applied by first understanding which asset is the priority or a focus of an organization. In general, an interview is held to the organization respondents who share the same responsibility of the asset by using IM^3 structure. Respondent is asked per dimension on how they assess their management maturity on a scale of ad-hoc to optimized. The interviewees were explicitly asked to mention practical examples to support their judgment on the estimated position in the IM^3 matrix by clear and concrete arguments. (Volker et al., 2013).

The results will then be compared between interviews and determine the general maturity of each dimension.

As mentioned in Table 1, the maturity model has five maturity levels which indicate the maturity levels of management. There are several dimensions or aspects of maturity that are focused on asset management which are:

Table 2 Infrastructure Management Maturity Matrix Dimensions

Asset Management Decisions	The ability of an organization to make a crucial decision which influences the asset capital value
Information Management	The availability and uses static and dynamic databases for decision making
Internal Coordination	The ability of an organization to coordinate and solve the problem between different departments
External Coordination	The ability of an organization to coordinate and solve the problem between different stakeholders in the project
Private Sector	The ability on commissioning, coordination and controlling the asset operation or execution from the outsourced private sector
Process and roles	The clarity of job definition and responsibilities within the organization
Culture and Leadership	The awareness, level of knowledge and support in an organization towards the related asset

The dimensions, presented in Table 2, represent the fundamental aspects of asset management which will be assessed by using the maturity levels. The use of the maturity model ends where the organization recognizes their maturity on asset management and does not evaluate the asset performance.

Past research was held in Rijkswaterstaat where the organization is assessed in two different years. This research (Volker et al., 2013), has an objective to know whether maturity model can be implemented in the Dutch public structure organization. The first year are meant to measure its initial maturity at a specific dimension. The second-year is done to examine the improvement compared to the prior maturity. The results show that the maturity model helps the organization to know their current performance and can be used as useful information for decision-making.

2.4 Information Management

Information management is one of the maturity indicators stated in IM3 which refers to sound registration of data as a basic pillar of asset management (Volker et al., 2013). The information management maturity is measured by the completeness, accuracy, and validity of data on assets and processes, stored in the organization to support decision-making (IAM, 2012). Information management maturity encompasses from the organization ability to distribute and store static information until the organization ability to fully integrates dynamic and reliable information that is accessible as part of the risk decision process.

In a decision process of flood defenses management, information towards asset is crucial to assure the asset condition and performance. Organization activity which involves asset is dependent towards the maturity of information management. It is not yet known the significance of information management towards organization ability to perform the activity. We believed that management dimensions are underlying management altogether in different perspectives. This notion led to an understanding that almost all management dimensions have a role in every organization activity. The general description of each management dimensions supports this believed where it is less likely that a certain activity only relies on a single management maturity dimension.

2.5 Knowledge Gaps

One of the main issues in the maturity model is the translation of management dimensions and levels towards asset performance. Previous studies have only focused on revealing the organization management maturity towards an asset. It has been proven to be effectively implemented in the case of Rijkswaterstaat (Volker et al., 2013) to identify the organization management maturity. The aforementioned research has shown potential improvement and proves that IM^3 can be implemented in practice.

The IM^3 provides a structure in measuring the management capability of an organization towards its assets. The measurement is a self-assessment where it is qualitatively measured by the respondent who is involved or responsible towards the selected asset (Vlad, 2017). Therefore, it is important to notice that the maturity model is a subjective measurement. The result is an assembled believed of their current management performance towards an asset. Since the management maturity will influence directly on the decision process, it is reasonable to hypothesize that maturity model can be extended to indicate the effect towards the asset lifecycle cost and performance. There have been no studies on the potential improvement of maturity model translation to asset cost and performance.

3 Methodology

This chapter outlines the research methodology used to obtain the model development. This research proposes a methodology by using Dynamic Bayesian Network with a hypothetical case. This chapter discusses the research strategy, semi-hypothetical case, Dynamic Bayesian Network, and output indicators.

3.1 Research Strategy

Dynamic Bayesian Network is believed to be able to quantify the probabilities of asset performance in conditional with organization asset management maturity. The research strategy, which is presented in Figure 2, begins by choosing the semi-hypothetical case which is aligned with the FAIR project. In this phase, the chosen case is elaborated by translating the case into a decision model. Then, the aforementioned decision model is translated to a Dynamic Bayesian Network model which quantifies the probability of the asset performance conditional to the organization maturity. After, the output of the network is further calculated with the assigned utility value, and the value of information is obtained.

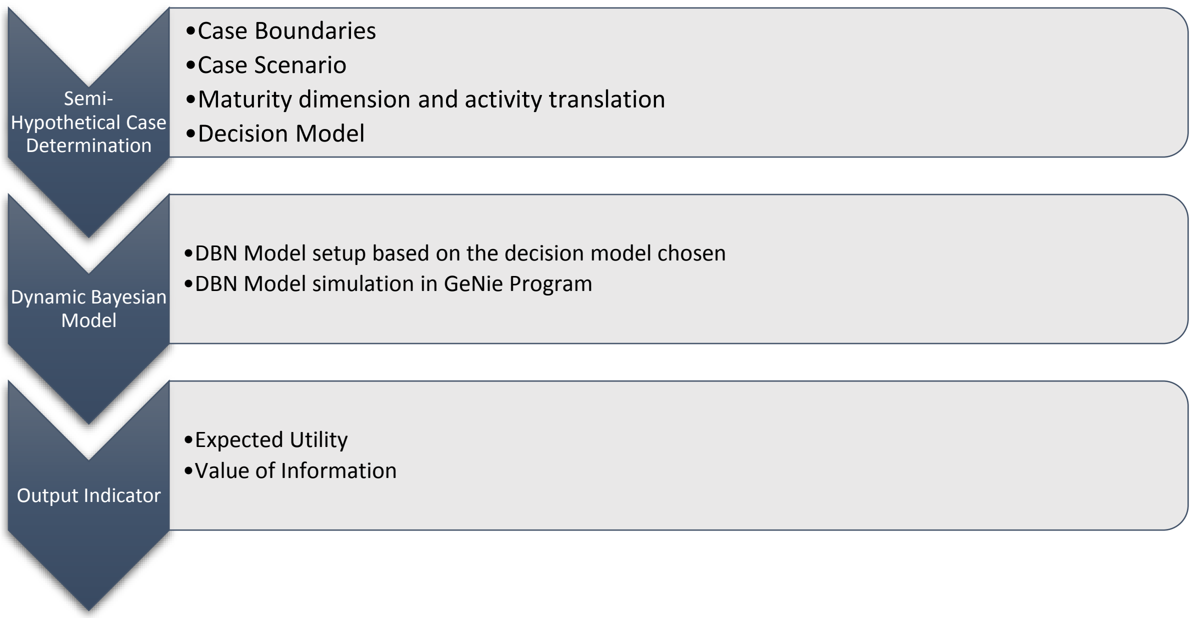


Figure 2 Methodology framework

3.2 Semi-Hypothetical Case Model

3.2.1. Boundary Condition

The investigation on maturity model extension requires a study case to explore how things can be done and to prove the aforementioned concept. Due to the limitation of data collection and time, this research uses a semi-hypothetical case. The hypothetical case should be clearly defined for its boundaries in which support the development of the case model which is displayed in Figure 3 Boundary condition of the semi-hypothetical case

BOUNDARY CONDITION	1. The asset is a flood defense structure 2. The asset performance can deteriorate and has a lifecycle maintenance activity 3. The asset condition can be acquired through information management activities 4. The deterioration asset can be translated into conditional or transition probability. 5. The case scenario focuses on organization decision process towards asset

Figure 3 Boundary condition of the semi-hypothetical case

3.2.2. Case Scenario

The semi-hypothetical case consists scenario of an organization decision process on an asset. This decision process is narrowed down to occur in the asset maintenance phase. In a decision process, information plays a vital role to support organization degree of believe. There are two significant performance indicators which are the quality of information and the use of information/data storing and distribution (W. Klerk et al., 2015) which is explored in the development of the model. From the boundaries condition, the case is developed into an asset information cycle which is conditional to the organization decision and activities. The information quality cycle is illustrated in Figure 4 disregarding the type of flood defense assets.

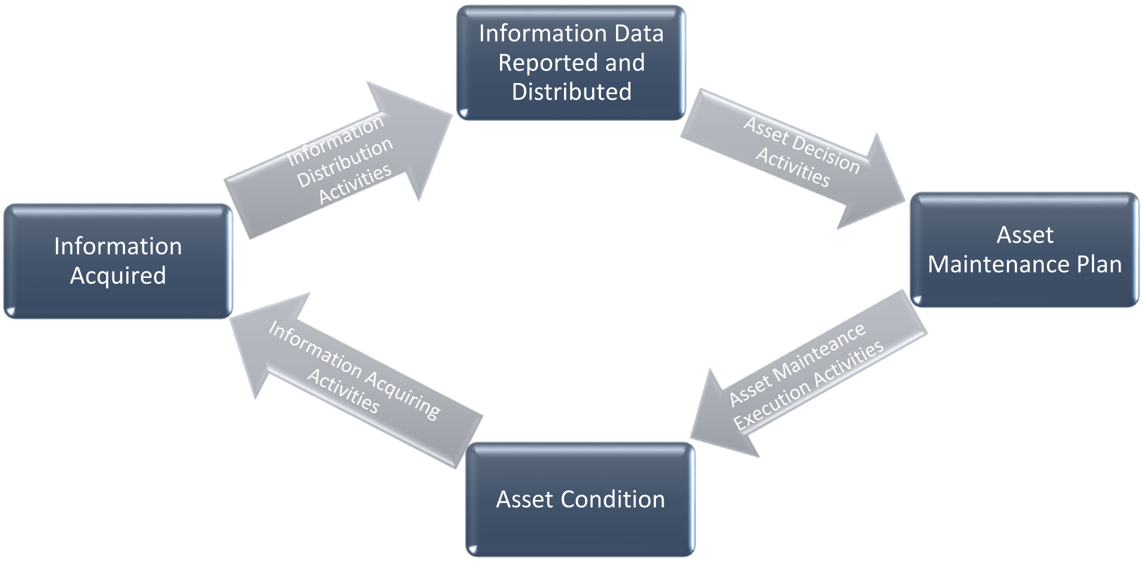


Figure 4 Asset information cycle in the maintenance phase

A flood defenses asset performance is known to degrade within time, and the asset manager has the authority decide their management approach toward their asset. In Figure 4, the information cycle is implemented in the asset maintenance lifecycle. There are four activities which are presented by arrows and four information quality at every stage of maintenance lifecycle in Figure 4.

The cycle starts from the organization acquires information their asset condition. Based on the organization ability, the organization will acquire a certain belief of asset condition. Then, organization organizes, store and distribute their set of belief inside their organization. Based on their ability, a new set of belief is available to be applied in the maintenance plan. Hence, the asset is maintained based on the information acquired and distributed by the organization.

This approach allows us to connect the organization decision process on asset maintenance with the organization management maturity and capability. Therefore, the translation on the influence of maturity towards the organization ability to perform activities are required, and it is explained in 3.2.3.

3.2.3. Management Dimensions and Activity Translation

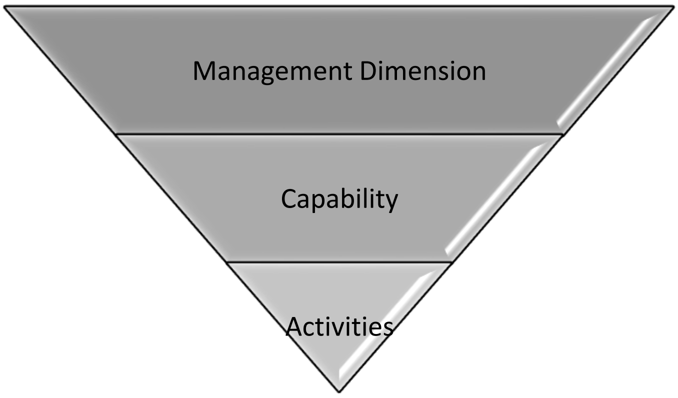


Figure 5 Management dimension, Capability and Activity relationship pyramid diagram

We believed that every management dimension has significance in every activity. Management dimension from IM3 has a broad definition and difficult to distinguish its significance to an organization able to execute certain activities. For instance, an inspection activity requires not only a single maturity but almost all maturity altogether. This complexity leads to the set-up of a new element, which relates both management dimension and activity execution; capability. Capability is the organization ability to perform an activity which corresponds solely to a single management dimension (see Figure 5). After obtaining the capability of each activity, we can subjectively determine which management dimension has significance towards an activity.

Table 3 Capability analysis for each activity

Activities	Capability	Dimension
Acquiring Information Acquiring information on asset condition. For example, inspection or acquiring data from another entity	Asset technical knowledge	Asset Decision Management
	Asset Information	Information Management
	Evaluative Culture	Leadership and Culture
	Passion and Integrity	
	Coordination Performance	Internal Coordination
	Organizational Framework	Roles and Process
Information Distribution and Management Information distribution in the organization. This activity influences the quality and the accessibility of information.	Information quality assurance	Information Management
	Information storage	
	Information distribution system	
	Evaluative Culture	Leadership and Culture
	Coordination Performance	Internal Coordination
	Organizational Framework	Roles and Process
	Job Responsibilities	
Asset Maintenance Plan/Intervention Plan The planning session based on the obtained information	Asset Technical Knowledge	Asset Decision Management
	Asset Capital Value Knowledge	
	External Interest Communication	External Coordination
	Coordination Performance	Internal Coordination
	Organizational Framework	Roles and Process
	Job Responsibilities	
	Evaluative Culture	Leadership and Culture
	Passion and Integrity	

In Table 3, activities are partitioned in several capabilities and connecting to the corresponding management dimension (this approach was inspired by the IAM asset management conceptual model). The findings can be seen that almost every management dimension contributes to each activity. It is logical to assume that an acquiring information activity on an asset requires not only information management but also good decision management, leadership, etc. But, the meaning in the management dimension is quite broad. Therefore, the author attempts to connect the management dimension and activity through capability.

The capability section elaborates through a specific ability of an organization in an activity. This elaboration shows the capability of an organization on an activity. For example, to perform an optimal acquiring information activity, the organization is required to have an excellent technical capability surrounding the asset, good information capability towards its asset, evaluative culture coordination capability and an effective framework within the organization.

Therefore, this elaboration of capability proves that activity requires several capabilities and every capability can be connected to a single management dimension.

The missing information of this notion is how significant each IM3 dimension influences the execution of the activity. This question is not furthered studied due to the limitation of time. For this research, we assume that asset decision management is a crucial IM3 since it involves the organization capability of the decision. Hence, asset decision management cannot be neglected. For simplicity of this research, asset decision management is set as a constant maturity, information management is assessed at every maturity, and other IM3 dimensions are neglected.

For further analysis of the management dimension influence towards activities, these are the consideration made for this research based on the previous analysis in Table 3:

- In acquiring information activity, asset technical and asset information and knowledge are set to be co-dependent. Asset technical capability is the asset manager ability to understand the physical and technical knowledge of their asset. Asset information and knowledge is the asset manager capability on providing the required information to support the activity planning. Hence, the activity relies on both the management dimension.

- In the Information Distribution and Management, the asset manager is managing, storing and distributing information inside its organization. There are several capabilities which are the reporting deliverance, the storage management, and the distribution system. The reporting deliverance refers to the accuracy and the completeness of its information. Storage management is the asset management capability to store and arrange to keep the quality of information. The information distribution management is the asset management capability to share information in the most informative way to support the activity. In this activity, asset decision management does not have a strong influence and assumed to be neglected.

- In the asset maintenance plan and maintenance execution, the information management is considered not to be significant. On the other hand, asset decision management has an active role in this activity to decide whether maintenance is required, or organization decides to do nothing based on the information acquired. Hence, it is crucial to consider asset management decision in this activity.

3.2.4. Semi-Hypothetical Decision Model

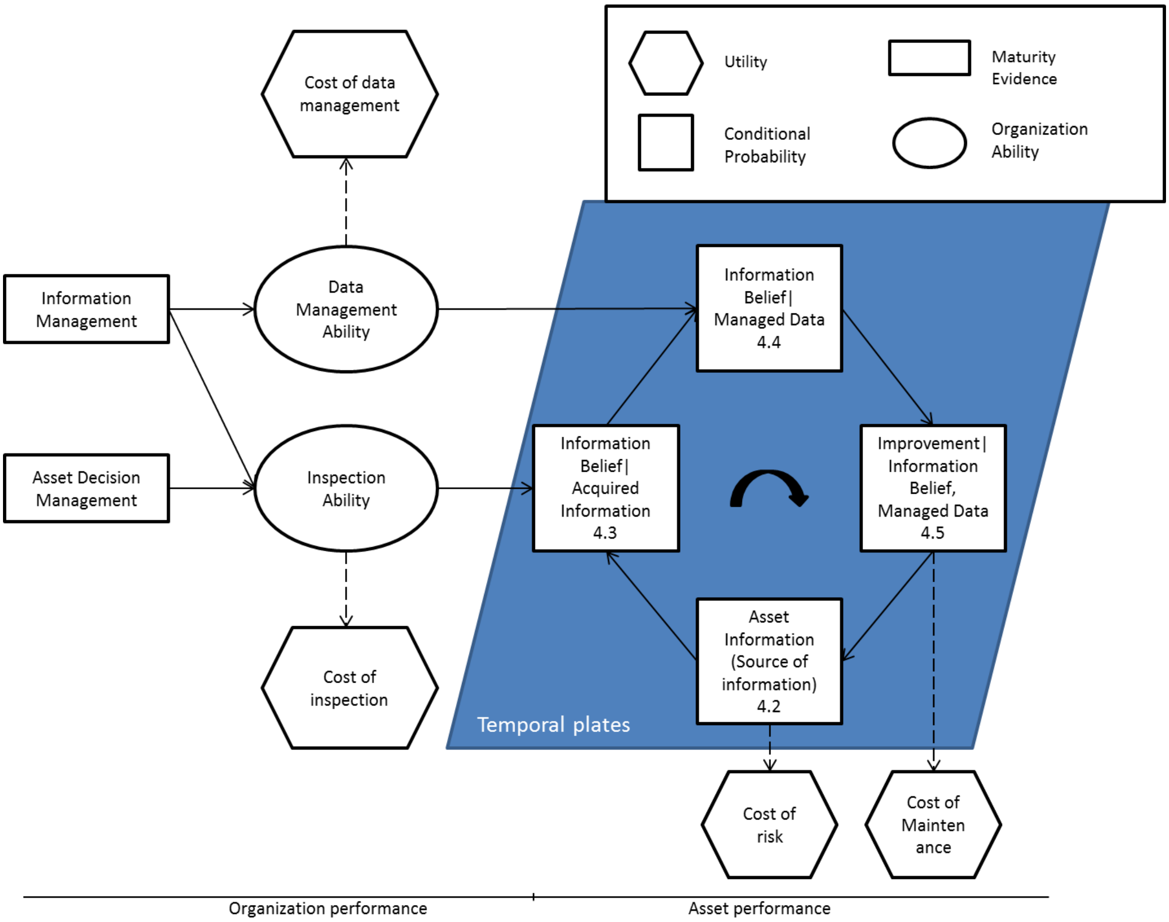


Figure 6 Dynamic Bayesian Network model of the hypothetical case involving the information management maturity levels, activity performance, and asset information cycle

After the case is determined, the dynamic Bayesian network can be developed based on the previous setup. Figure 6 shows the illustrated Dynamic Bayesian Network Model which consists of management dimensions, organization ability in performing activities and information cycle (Dynamic Bayesian Network is explained in chapter 3.3). The organization ability on performing activities are conditional to the maturity of organization management, and the asset condition is conditional with organization ability in storing and acquiring information. The information cycle is set to be dynamic, which has a constant change in time. The change depends on the case chosen. For this research, the change in time refers to the deterioration rate of the flood defenses asset in a certain time-steps.

For this research, we use Genie Modeler to simulate the model. GeNie Modeler is a tool for modeling and learning with Bayesian Networks, Dynamic Bayesian Networks and influence diagrams. This program features to graphically model and simulates the Dynamic Bayesian Network. It has been used widely by both academia and industry. This program allows us to simulate the asset lifecycle cost conditional with the organization management maturity.

3.3 A Brief Dynamic Bayesian Network

This research applies Dynamic Bayesian Network (DBN) to estimate the annual cost and performance of an asset conditional to the asset management. The semi-hypothetical case chosen involves a decision process of an organization towards of a deteriorating flood defense performance during its lifecycle. Therefore, in order to apply the time variable, this model requires a Bayesian Network with multiple time-frames. DBN is an extension of the Bayesian Network combined with the Markovian property. This section explains briefly on Bayesian Network, Dynamic Bayesian Network, and Markov Chain.

3.3.1. Bayesian Network

Bayesian Network is a sequence of causal probability relationship among set random variables, their conditional dependences and provides a compact representation of a joint probability distribution is called Bayesian Network (Scutari et al., 2011). Bayesian Network can be presented as a probabilistic graphical model which consists of graphs in which nodes represent random variables and arcs represent conditional independence assumption.

Bayesian methodology is known as a learning process which is represented in a set of probabilities as the degree of belief. The learning process involves revising the degree-of-belief in the truth with the proposition of new information through Bayes' Theorem.

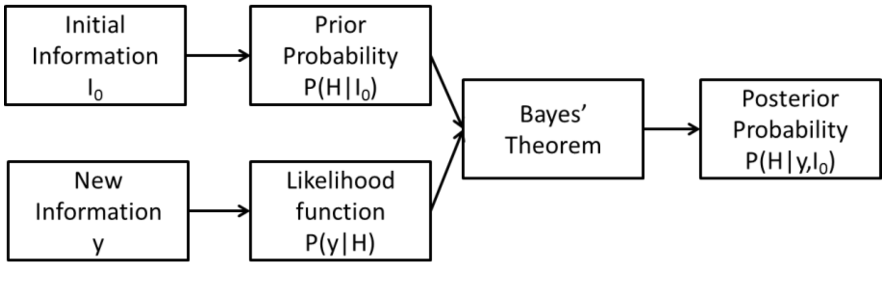


Figure 7 Process of revising probabilities of a certain belief given new information provided by using Bayes' Theorem (Zeller, 1996)

In Figure 7, it displays the process of revising probabilities of a certain belief given new information provided. This explanation and the following example are taken from Zeller (1996) which is compliant for this study. Given the initial information I_0, our prior probability or degree of belief $P(H|I_0)$ is given with a particular proposition H. New information y, given H, gives a certain likelihood function $P(y|H)$ where it can be combined with prior probability through Bayes' theorem resulting a posterior probability $P(H|y,I_0)$. The posterior probability has a dependency on the prior beliefs and the additional information. Through Bayes' theorem, the prior probability is inferred based on the additional information and transformed to the posterior probability.

The application of Bayesian Network consists of giving evidence to one or more nodes of the model which results to a belief change. Condition dependences are causal in both directions, from cause to effect and from effect to cause. Three possibilities to connect between nodes (see Figure 8).

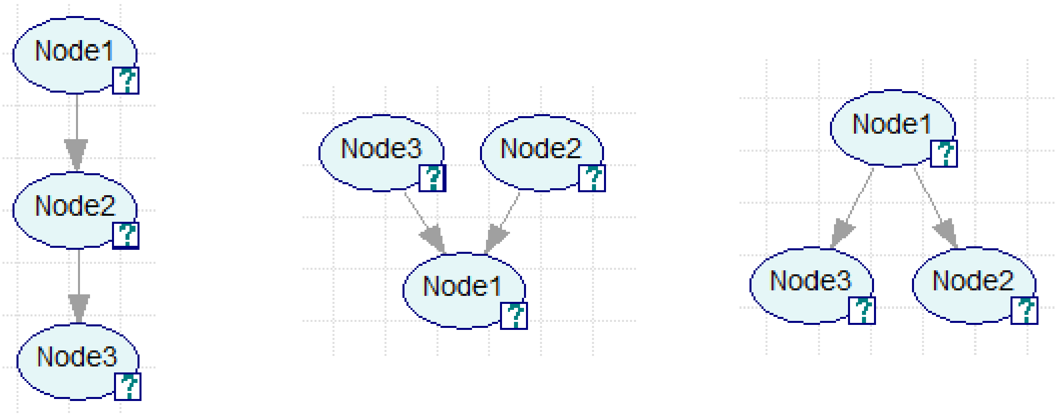


Figure 8 The condition dependencies type: linear connection (left), convergent connection (middle), divergent connection (right)

A linear or serial connection is the situation where variables are connected independently in a sequence. The convergent connection is where two or more different nodes influence a node. Divergent is a situation where nodes are influencing two or more nodes.

A conditional dependencies graph tells us about the structure of the probabilistic domain but not the numerical properties. These are presented as a conditional probability table (CPT). CPT is the representation a conditional probability of a single variable dependent on others. CPT reveals a collection of a probability distribution over the child node which each node are connected to a different parental configuration. These probability represents the parent and child dependency and can be written like the example shown below:

Let us denote that *event A* and *event B* is the parental node whereas *event X* and *event Y* is assumed to be the child node, and the conditional probability is written as *a,b,c* and *d*. The probability of an event in the child nodes occur dependent to the parental nodes are presented in Table 4. This size of the matrices or tables depends on the number of variables considered in the network.

Table 4 Conditional probability table (CPT)

Events	A	B
X	$p(X\|A) = a$	$p(X\|B) = b$
Y	$p(Y\|A) = c$	$p(Y\|B) = d$

3.3.2. Dynamic Bayesian Network

Dynamic Belief Network (DBN) is a belief network system that is dynamically changing or evolving over time. This model gives insight into the behavior of the system as time proceeds (Milajlovic et al., 2001). In the DBN, every time slice of a temporal model corresponds to a particular state of a system and have a particular transition probability.

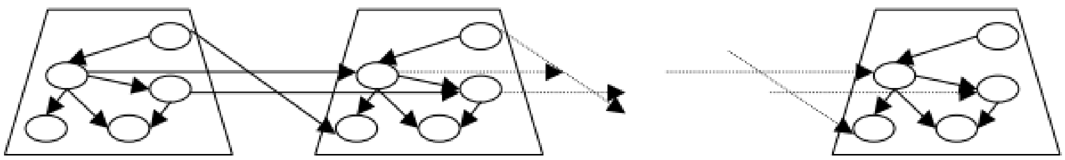


Figure 9 Dynamic Bayesian Network temporal plates (Milajlovic et al., 2001)

In Figure 9, it is an illustration of a dynamic Bayesian network which consists of a sequence of submodels each representing the system at a particular time step. Every system is connected by temporal relation, which is represented by arcs. Dynamic Bayesian Model is usually used for a time series modeling which satisfies the Markovian condition where the future is independent of the past given the present (Milajlovic et al., 2001).

3.3.3. Markov Chain

Markov chains have been used in civil engineering fields to visualize and model the uncertain deterioration rate in physical structure such as pipe deterioration (Micevski et al., 2002).

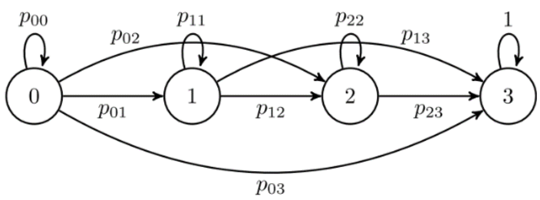
Markov chain is a discrete-time stochastic process $\{X_n, n = 0,1,2,...\}$ which describes the movement between a finite number of states and for which the Markovian property holds (Kallen, 2007). The Markov property says that, given the current state, the future state of the process is independent of the past states. Hence, the future states only depend on the current condition. The conditional probability table of moving into state *j* at time *n+1* given that at the current time *n* the object in state *i* is given by (Frangopol et al., 2004):

$$P_{ij} = \Pr\{X_{n+1} = j \mid X_n = i\} \tag{1}$$

In order to define the Markov Chain X_n, it is necessary to determine the transition probabilities between all possible condition state which are paired. If there are N states, then the matrix will have a size of N x N.

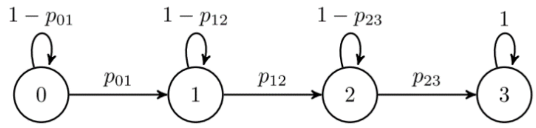
$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1N} \\ P_{21} & P_{22} & \cdots & P_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ P_{N1} & P_{N2} & \cdots & P_{NN} \end{bmatrix} \tag{2}$$

Equation (2) represents a transition matrix which gives information of transition probability at each time unit. The transition probability can be determined based on its nature of occurrence which can be measured and mathematically obtain. There are several types of graphic representation of the Markov process in practice which are progressive, and sequential Markov processes. A progressive discrete time Markov process is a graphical representation of a system that can leap forward or jump a state in time (see Figure 10). A sequential Markov process (see Figure 11) represents a consecutive relation of each state, by means that the state cannot leap another state.



$$P = \begin{bmatrix} p_{00} & p_{01} & p_{02} & p_{03} \\ 0 & p_{11} & p_{12} & p_{13} \\ 0 & 0 & p_{22} & p_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 10 Progressive Markov processes



$$P = \begin{bmatrix} 1-p_{01} & p_{01} & 0 & 0 \\ 0 & 1-p_{12} & p_{12} & 0 \\ 0 & 0 & 1-p_{23} & p_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 11 Sequential Markov processes

Both examples have four successive conditions where the state three is referred as an absorbing state or the last state of the system which has certainty for the state to remain. All other states are called as a transient state which has a probability to remain or to leap into another state.

3.4 Output Indicator

In this section, we assume that the model has been executed. The DBN model produces a certain belief of asset lifecycle performance. This result can be translated into the expected utility of the model and be compared based on the asset expected annual cost and value of information.

3.4.1. Expected Utility

Expected utility can also be called as probability-weighted utility theory. This approach is used in the decision-making under risk situation which consists of alternatives or choices, probability, and utility value. For each alternative, a specific utility value is assigned and probability used as weight. The product of probability and the utility value results into an expected utility. This concept also can be stated in a more general manner: let there be t timesteps which are associated by a utility (u_n) and a probability (p_n). The expected utility is calculated as follows (Hansson, 2005):

$$E(U) = p_1 u_1 + p_2 u_2 + \cdots + p_n u_n \quad (3)$$

Expected utility is the sum of the product of utility and probability for every time-step. In this research, the utility refers to the asset risk, cost of maintenance, cost of inspection and cost of data management. The outcome of this assessment is a graphical display of asset expected cost and performance for each maturity scenario during its lifetime.

3.4.2. Value of Information

Value of Information (VOI) is the mathematical framework to assess the value of specific information to an existing system (Straub, 2014). It is a method that evaluates the benefit of acquiring additional information to reduce uncertainty in a specific decision-making process (Lawrence, 1999; Marchese et al., 2018). This method is known to be the extension in statistical decision theory (Howard, 1962). The concept is to acquire the opportunity value between a decision making with present information relative to the anticipated value of the same decision with additional information.

VOI analysis is applied to identify the opportunity cost between information management maturity levels. In a different management maturity, organization ability and asset performance are affected. This analysis will give information on which maturity management that would be beneficiary for a particular condition. The result of VOI helps decision makers identify whether additional information is needed or to decide with the current uncertainty (Marchese et al., 2018).

To illustrate this concept more comprehensible, consider a simple example of a physical asset during its function which failure can occur, which is similar to this research. For simplicity, the time of failure is neglected, and the organization has the responsibility to do maintenance based on the acquired information. The acquired information is vital towards the organization maintenance decision. If the organization decide to acquire additional information, the prior set of belief is updated to a posterior set of belief. Hence, the degree of maintenance with a posterior set of beliefs is different from the degree of maintenance with a prior set of belief. The degree of maintenance has a direct impact on the cost of failure.

The value of information can be written as below:

$$VOI = (C_{prior}) - (C_{posterior}) = (C_f + M)_{prior} - [(C_f + M)_{posterior} + C_{Info})] \tag{4}$$

VOI	= Value of Information
C_{prior}	= The cost of the asset before maintenance and additional information
$C_{posterior}$	= The cost of the asset after maintenance and additional information
C_f	= Failure cost of the asset
C_{Info}	= Additional information cost
M	= Maintenance cost

In principle, the result should represent the value of information of the additional information. The result shows the value of the additional information. If the results indicate a negative value, this indicates that the information is not beneficial. On the other hand, VOI can be positive and describe the significance of the additional information in a particular scenario.

3.5 Summary

Asset lifecycle cost and performance conditional to the organization information management maturity can be illustrated by using Dynamic Bayesian Network. This research uses the GeNie Program (see 3.2.4) as a platform to graphically model and simulates the DBN. Due to the limitation of data and time, a semi-hypothetical case is chosen (see 3.2) to see how the model behaves. The chosen scenario (see 3.2.4) is the organization decision process in the maintenance phase conditional to organization information management maturity. The expected utility (see 3.4.1) can be calculated based on the DBN output and analyzed using Value of Information (see 3.4.2).

4 Model Setup

4.1 General Setup

There are several types of flood defenses structure available for this research, but it is important to consider also the applicability and the relevance of the case in the FAIR project. Therefore, the asset scenario chosen is grass revetment on a dike. A dike is a common flood defense structure. Dikes are typically located at the river edge or shore to provide safety against flooding events which may be caused by high precipitation or astronomical tide. (S.N. Jonkman et al., 2017). A typical dike consists of a sand core with sublayer clay and grass revetment. Grass revetment is a sustainable design that has a function to strengthen the dike from erosion. (Rinsum, 2018)

A good condition of grass revetments gives an extra strength to avoid erosion when high water occurs. Grass revetment, according to the Technische Adviescommissie voor de Waterkeringen (Rijkswaterstaat, 2017), is the grassland vegetation rooted in soil. Grass revetments can deteriorate due to high water events, animal burrowing, or severe weather. Due to the limited of grass recover studies, the scenario is narrowed down to the winter season where grass has a small likelihood to recover or grow.

Table 5 Asset General Information

Asset	Grass revetments during the winter season
Dike Length (km)	1
Timesteps	Monthly
Inspection Frequency	Monthly
Asset Value (Consequences)	10 billion Euros
Probability Failure Required	10^{-3}

4.2 Asset Initial Condition and Deterioration

The grass deterioration can be initiated by a different cause, such as wave interaction, current interaction, extreme weather, and animal burrowing. The influence of currents is typically small and can be neglected (Rinsum, 2018). The influence of wave impact and wave run-up is the most significant load, especially in the outer slope where the impacting wave creates high pressure in a short period (Rijkswaterstaat, 2017).

Most grass degradation is gradual and cumulative without the presence of maintenance. Therefore, the transition grass quality in time does decrease with the assumption that only intervention can increase the grass quality.

Figure 12 Examples of references picture for different grass condition. The grass condition of the left picture is in the closed condition; the middle is an open condition, and the right is the fragmented condition. Images are taken from Het Waterschapshuis (2016)

There are three different grass condition (see Figure 12 Examples of references picture for different grass condition. The grass condition of the left picture is in the closed condition; the middle is an open condition, and the right is the fragmented condition. Images are taken from Het Waterschapshuis (2016)) is common in practice which is a closed condition, open condition, and fragmented condition. In Table 6, it is presented the general information on the grass condition. In the closed condition, the reliability of the grass is high in which translate that erosion will be less likely to occur. For the grass with an open condition, the grass revetments are not in perfect condition. Holes or weak grass are detected and slightly prone to erosion. Therefore, the open condition will have a higher reliability than the closed condition. The fragmented condition is not mentioned in the schematization of grass cover from the Water Authority of the Netherlands. However, in recent research (W. J. Klerk et al., 2018), a fragmented condition is considered as a parameter. Fragmented condition refers the low-quality grass where it is fundamentally unacceptable and are significantly prone to erosion or stability failure.

Table 6 General information on grass condition for the hypothetical case

Condition	Closed	Open	Fragmented
Critical Velocity (m/s)	6.6*	4.3*	2
Reliability	10^{-6}	10^{-5}	10^{-2}
Critical Discharge (m^3/s)	0.07*	0.04*	0.01
Risk Failure (Euro)	100	1.000	10.000.000
*based on the Schematiseringshandleiding grasbekleding (Rijkswaterstaat, 2017)			

The grass degradation at each timestep accumulates if the asset manager does not intervene. In practice, the determination of transition probability is difficult due to the uncertainty of deterioration events and uncontrolled variables such as soil fertility. Due to the complexity, the transition probability value is set based on expert consultation and consideration.

The grass transition probability is determined by considering the time step length of the model. Thus, the transition probability of grass condition within a month is higher than the transition with a weekly timestep. For this research, three transition probabilities are considered as scenarios. Transition probability of grass condition scenarios are written as determined below:

Table 7 Transition probability of grass condition scenarios for every time steps

Scenario	Initial Condition	Transition Probability at t+1		
		Closed	Open	Fragmented
1	1.1 Closed	0,99	0,025	0,005
	1.2 Open	0	0,99	0,03
	1.3 Fragmented	0	0	1
2	2.1 Closed	0,98	0,01	0,01
	2.2 Open	0	0,98	0,02
	2.3 Fragmented	0	0	1
3	3.1 Closed	0,96	0,02	0,02
	3.2 Open	0	0,96	0,04
	3.3 Fragmented	0	0	1

The transition probability, as shown in Table 7, has a progressive Markov process. By means, the grass in closed condition can transition to the fragmented condition. It is realistic to assume that a grass revetment during the winter will only have a small likelihood for its condition to deteriorate. Hence, the probability that grass condition will remain the same after a week has always a high value compared the probability that the grass will deteriorate.

4.3 Acquiring Information Activity

There are several approaches to acquire information on a flood defenses asset condition. In general, acquiring information for the grass revetments condition is done by site inspection. The goal of inspection is to detect and report the corresponding asset condition without losing any information. This activity corresponds to the planning stage and the execution of acquiring information which involves the asset management planning and operational team. During the maintenance phase, the organization requires enough information to support their decision process.

The quality of inspection has a dependency on asset decision management and information management maturity (see Table 3). An optimized maturity over this activity may lead to a consistent and reliable information outcome and vice versa for an ad-hoc maturity. For this activity, it is assumed that the asset decision management dimension has a more significant rather than information management. Five levels are considered in this model. We assume that every inspection ability is classify based the consistency, completeness, and accuracy of the information acquired (see Table 9 and Table 11)

Table 8 Inspection Ability Description

Organization inspection ability	Inspection Ability Description
Impromptu Inspection	This organization has ad-hoc decision management and information management. The organization does not know their deteriorating asset. There are no activities that concern on the asset condition. Even if the organization inspects its asset, the information obtained is inaccurate due to lack of planning and initiative.
Poor Inspection	The organization has repeatable decision management. This ability refers to an organization that has a lack of consistency in their inspection schedule and procedure. The organization inspection is executed without a standard procedure.
Planned Inspection	The organization has a standard procedure and regular schedule for the inspection activity. At this level, the organization is aware and has enough knowledge to recognize the required asset information for a planned inspection. Due to additional information requirements, the organization may need some extra personnel or equipment.
Advanced Inspection	The organization has a deep understanding of their asset which leads to an advanced method of inspection. The inspection budget is higher than the previous level due to the required extra information.
Optimized	The organization has an optimal approach to inspection procedure, method and has a more optimal budget

Table 9 Inspection Ability

Organization inspection ability	Visual	Geo-referenced	Root Analysis
Impromptu Inspection	X		
Poor Inspection	X		
Planned Inspection	X	x	
Advanced Inspection	X	x	x
Optimized	X	x	X

The conditional probability table matrix in the model is determined based on the expert consultations (see Table 10). The conditional probability table matrix in this activity refers to the accuracy of the acquired information conditional with the information maturity. The significance of information management maturity towards acquiring information activity is defined based on the consistency and efficiency of the inspection method. Lack of information in the inspection planning may lead to an ineffective inspection where only a few critical detections of bad grass quality can only be informed.

Table 10 Conditional probability table matrix of information quality at every organization inspection's ability

Organization inspection ability		Impromptu Inspection			Poor Inspection			Planned Inspection			Advanced Inspection			Optimized		
Grass Condition State		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
Acquired Iimpromptun	Closed	0.34	0.33	0.33	0.5	0.25	0.25	0.75	0.12	0.12	0.95	0.05	0	1	0	0
	Open	0.33	0.34	0.33	0.25	0.5	0.25	0.13	0.75	0.13	0.03	0.95	0.02	0	1	0
	Fragmented	0.33	0.33	0.34	0.25	0.25	0.5	0.12	0.13	0.75	0	0.05	0.95	0	0	1
C= Closed ; O= Open; F=Fragmented																

The inspection cost, shown in Table 11, is developed based on the average cost of inspection (Rijke et al., 2014). The inspection cost can be more factual and accurate with the actual cost of inspection data of a different organization. For this study, the cost is determined based on expert consolations, and we tailored the costs found by Rijke and Hertogh to apply to our particular case.

Table 11 Organization inspection ability cost and conditional probability

Organization inspection ability	Cost per Inspection/km	Conditional probability table matrix /Accuracy
Impromptu Inspection	€ 315.00	0,33
Poor Inspection	€ 360.00	0,5
Planned Inspection	€ 450.00	0,75
Advanced Inspection	€ 630.00	0,95
Optimized	€ 540.00	1
Assumption made: Average cost per inspection: € 450 /km		

4.4 Data Management and Distribution

Every organization must assure that information is available and accurate at any time through data management. Data management is the practice of organizing and maintaining data to meet the required needs. Every organization has a different scale and investment in data management which makes it hard to approximate. Therefore, in this research, data management success is measured from the information accuracy, storage, and information accessibility.

From the assessment in Table 3, the information management has a high dependency towards this activity. Therefore, information management maturity has a linear relationship with the data management activity. In order to separate different maturity influence towards the activity, five levels are determined.

Table 12 Data management organization ability

Data Management Ability	Data management description	Total Data Storage (TB)	Monthly Cost (€) /km	Conditional probability table matrix	Accessibility
Lack of Data Management	In this level, the organization does not have expertise in the field. Where only general information is only stored.	1	€ 41.67	0,6	slow
Accessible	Since the information management maturity is at repeatable. The quality information stored does not improve significantly, but the accessibility has improved.	1	€ 62.50	0,7	normal
Accessible and Georeferenced	At this stage, the information management maturity is at standard. This ability refers to an organization that has a standard procedure to store and distribute information with fair accuracy.	1.3	€ 108.33	0,8	normal
Advanced Information and Centrally Available	The organization has large storage management, advanced data distribution and has enough expertise	1.7	€ 180.00	0.9	fast
Optimal	The organization has advanced data management. Information is well stored and accurate	1.7	€ 200.00	1	fast
Assumption made: - Average total data storage per company: 150 TB (IT Key Metrics Data, 2015) - Average total data information on dike: 20TB/15 km or 1.3 TB/km (Assumption) - Average price data management per terabyte: 1000 € /TB /year (IT Key Metrics Data, 2015)					

The five levels of data management, as shown in Table 12 Data management organization ability, are determined based on the amount of storage, accuracy, and accessibility. The highest level refers to an organization that can store sufficient amount and quality of information and is easily accessible. The lowest level of data management refers to an organization that has a poor procedure which jeopardizes the information quality, hardly accessible and insufficient amount of storage.

In the maintenance phase, the information accessibility is assumed not to be a significant aspect. It is assumed that the organization maintains their asset regularly and does not need immediate access to the asset information. Therefore, only information quality is the focus of this model. At this stage, the information is accessible inside the organization which will be exercised during the maintenance design.

Table 13 Conditional probability table at each organization data management ability

Data Management Ability		Lack of Data Management			Accessible			Accessible and Georeferenced			Advanced Information and Centrally Available			Optimized		
Information Acquired from Inspection		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
Accessible Information	Closed	0.6	0.2	0.2	0.7	0.15	0.15	0.8	0.1	0.1	0.9	0.05	0	1	0	0
	Open	0.2	0.6	0.2	0.15	0.7	0.15	0.1	0.8	0.1	0.05	0.9	0.1	0	1	0
	Fragmented	0.2	0.2	0.6	0.15	0.15	0.7	0.1	0.1	0.8	0.05	0.05	0.9	0	0	1
C= Closed ; O= Open; F=Fragmented																

4.5 Asset Maintenance

The asset decision maintenance activity is the phase where asset management responds and design the maintenance measures according to the available information in the organization. At this stage, the asset management relies on their technical and capital knowledge of their asset. Capital knowledge is the knowledge of the asset management about the asset capital value.

The maintenance activity will have a dependency on the asset management decision. Since, for this research, only information management is assessed. The asset management decision is set to be constant in standard maturity. It implies that the organization decision on maintenance is assumed to have only two different output of decision. These options are improvement or do nothing

In the ‘improvement’ alternatives, the asset management decides to improve and repair the deteriorated grass that has been detected to underperform which if the grass condition is indicated as fragmented. The improvement is assumed to be executed perfectly where the asset condition is improved to a closed condition. Whereas in ‘nothing,’ the organization decides to do nothing, and the asset condition does not change.

The cost of maintenance is assumed to be independent where the organization information management maturity does not have an influence. The value chosen is based on the literature findings on the average cost of dike maintenance in the Netherlands (Rijke et al., 2014). The cost of maintenance refers to the amount of money spend of an organization on maintenance work every single month. These are the assumption value made for the cost of maintenance:

- Grass reparation cost: 8000€/km/year (Rijke et al., 2014)
- Length of the dike: 1 km
- Total cost: 660 €/maintenance/month

4.6 Organization Ability and Management Dimension Relationship

Table 14 Organization Ability and Management dimension Relationship

Information Management	Asset Decision Management	Organization Ability	
		Data management activity	Acquiring Information Activity
Ad-hoc	**Standard**	Low Data Accessibility	Poor Inspection
Repeatable	**Standard**	Accessible	Poor Inspection
Standard	**Standard**	Accessible and Georeferenced	Planned Inspection
Well Managed	**Standard**	Centrally Available	Planned Inspection
Optimized	**Standard**	Optimized	Advanced Inspection

In this model, there are five different alternatives of organization ability towards an activity through two different management dimensions. Therefore, there are five scenarios which are simulated. At every information management maturity, the organization ability varies, particularly to an activity that has a strong dependency towards information management.

Table 14 shows a matrix of organization ability at different information management maturity. The matrix is developed based on the previous elaboration and understanding of each activity and capability. The organization ability to acquire asset information is not profoundly affected by information management maturity. Based on the elaboration in chapter 4.3, the organization inspection ability relies more on the decision management maturity dimension. Hence, since the organization has a standard decision maturity, the output of the inspection ability is limited. It is logical to assume that a standard management maturity organization will not have an impromptu inspection.

The organization, which has information management maturity lower than standard, are likely to have an inadequate inspection, due to inconsistency and lack of asset information. On the other hand, organization, that has optimized information management, would have more information to plan an effective and efficient inspection.

Information management maturity dimension has a high influence towards the organization ability to manage data. Based on the elaboration in chapter 3.2.3, information management encompasses strongly the required capability of an organization to perform this activity. Therefore, the organization ability level is set to follow the organization information management maturity.

4.7 Model Summary

After the parameter of the model has been set, the Dynamic Bayesian Network model is created by using the GeNie program (see Figure 13). There are 14 nodes with different functions, in which ten nodes are configured inside of the temporal plate. A temporal plate is a tool provided in the GeNie program to replicate the BN at the different time steps or Dynamic Bayesian Network.

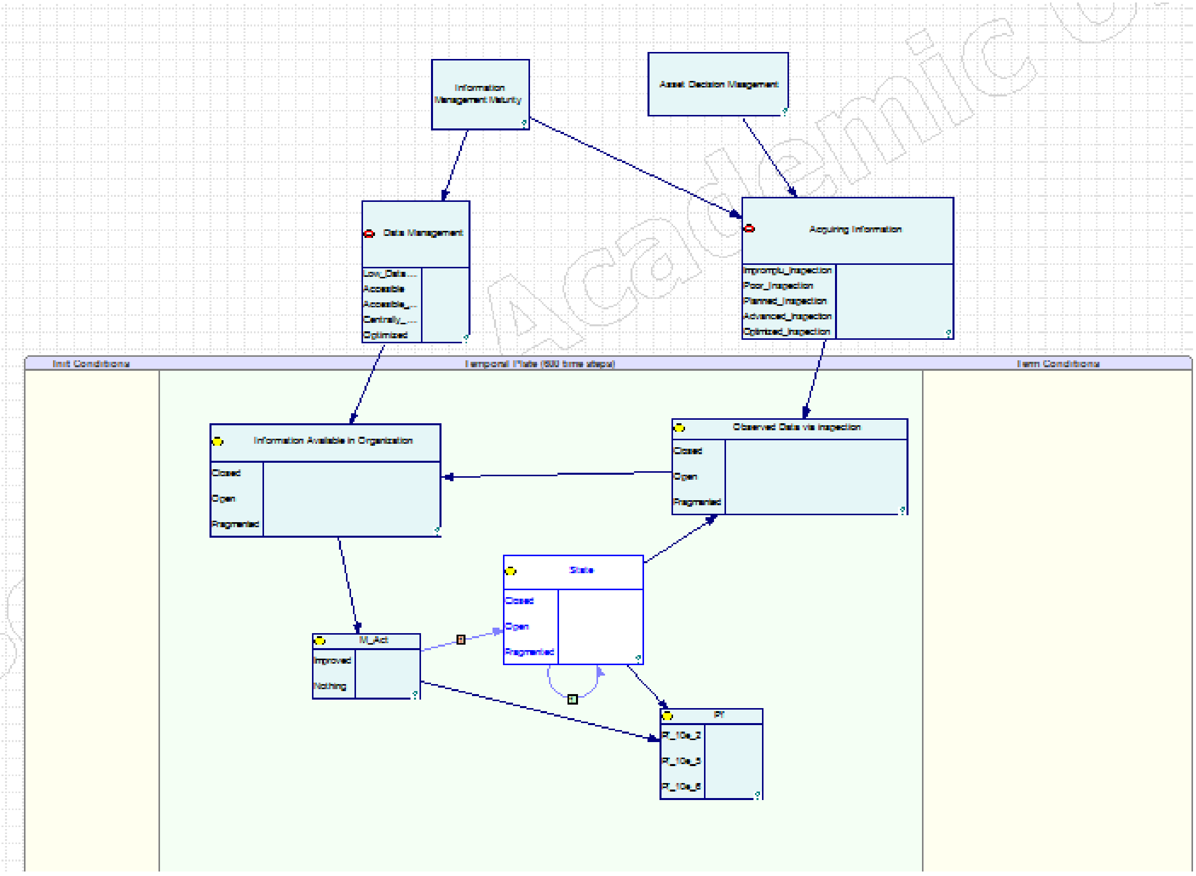


Figure 13 Dynamic Bayesian Network Model in the GeNie Modeling program

Few remarks needed to be explained:

- The arrow indicated in the model shows the dependency on the components over the timesteps. The grass state and improvement have a unique function of having an arrow with an order of 1. The order refers to the influence towards the directed nodes at the next timesteps (t+1). In other words, the current grass state and improvement will influence the grass state at the next time steps.

- The maturity levels and activities are configured outside the temporal states by assuming, during the asset lifetime, the organization maturity and ability does not change in time.

- The simulation is done in three different initial states and five different maturity levels of information management.

- The conditional probability table is set based on the previous case development (see 4.3, 4.4, and 4.5). The simulated conditional probability table values are displayed in the Appendices A .

- The utility nodes are illustrated in the trapezium nodes. There are four different utility nodes which are the cost of failure, cost of organization data management, cost of inspection and cost of maintenance/improvement. Total cost is the summation of utilities at every time steps.

$$\sum C_i = C(f)_1 + C(Dm)_1 + C(In)_1 + C(\mathrm{Im})_1 + ... + C(f)_i + C(Dm)_i + C(In)_i + C(\mathrm{Im})_i \quad (5)$$

$\sum C_i$	= Total utility cost at every time steps
$C(f)_i$	= Failure Risk at a specific time step
$C(Dm)_i$	= Data management cost at a specific time step
$C(In)_i$	= Cost of inspection at a specific time step
$C(\mathrm{Im})_i$	= Cost of improvement at a specific time step
I	= time step

  - One of the utilities is the risk of failure. The risk of failure is calculated by having the product on the state condition probability and the failure cost at each state which are provided below:

Table 15 Risk failure for GeNie model

Probability of failure	0.000001	0.00001	0.01
Risk failure	€1000.00	€10,000.00	€10,000,000.00

  - The cost of data management differs at every ability level. The cost-utility is determined to increase along with the organization ability (see chapter 4.4). The cost increase is initiated due to the increase in complexity, accuracy, and accessibility of the organization information system.

Table 16 Cost of organization data management at every ability level for GeNie model

Lack of Data Management	Accessible	Accessible and Georeferenced	Central Available	Optimized
€ 41.67	€ 62.50	€ 108.33	€ 180	€ 200

- The cost of acquiring information also differs at every ability. The cost is determined based on the consideration made in chapter 4.3. The organization with an optimized ability has the same technical approach an organization that has advanced inspection ability, but the optimized organization is more efficient in the expenditure.

Table 17 Organization cost of acquiring information at every ability level for GeNie model

Free-Will Inspection	Poor Inspection	Planned Inspection	Advanced Inspection	Optimized
€ 315	€ 360	€ 450	€ 630	€ 540

- The cost of the improvement is set based on desk research. The cost improvement does only account a single option of improvement. Therefore, the cost of improvement has only two options which are the improvement activity, or the organization does nothing.

Table 18 Cost of improvement for GeNie model

Improvement	Nothing
€ 650	0

5 Results and Analysis

The DBN model simulated from the GeNie modeling program. The result shows the expected utility cost of every time-steps of the model. The model is presented in two approaches which are the asset lifecycle cost and value of information. To analyze the expected cost utility over the lifetime, we acquire the annual cost which is the sum expected cost of every 6-time steps. To recall, the model considers only the maintenance activities during the winter season which is assumed to be represented in six time-steps. The value information is to analyze the difference in asset cost and performance in different information management maturity.

5.1 Asset Annual Cost

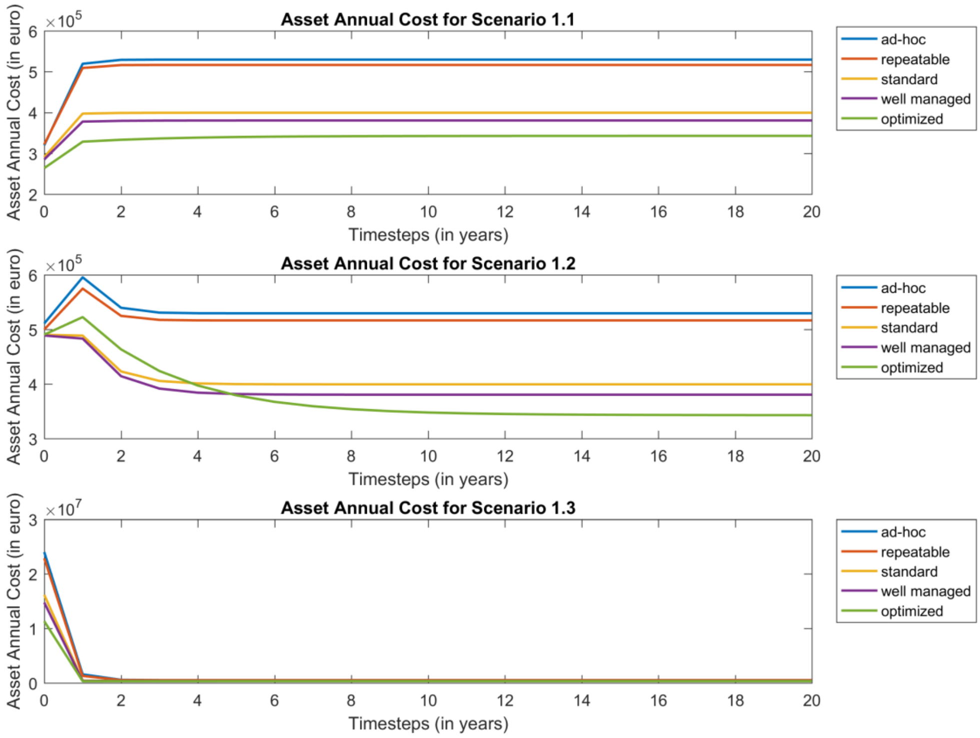


Figure 14 The graph displays the expected annual cost results of the model with respect to the asset lifetime. The result shows in the total asset cost (shown in y-axis) for every winter season or yearly (shown in the x-axis) for scenario 1. Other scenario results are displayed in the Appendices B

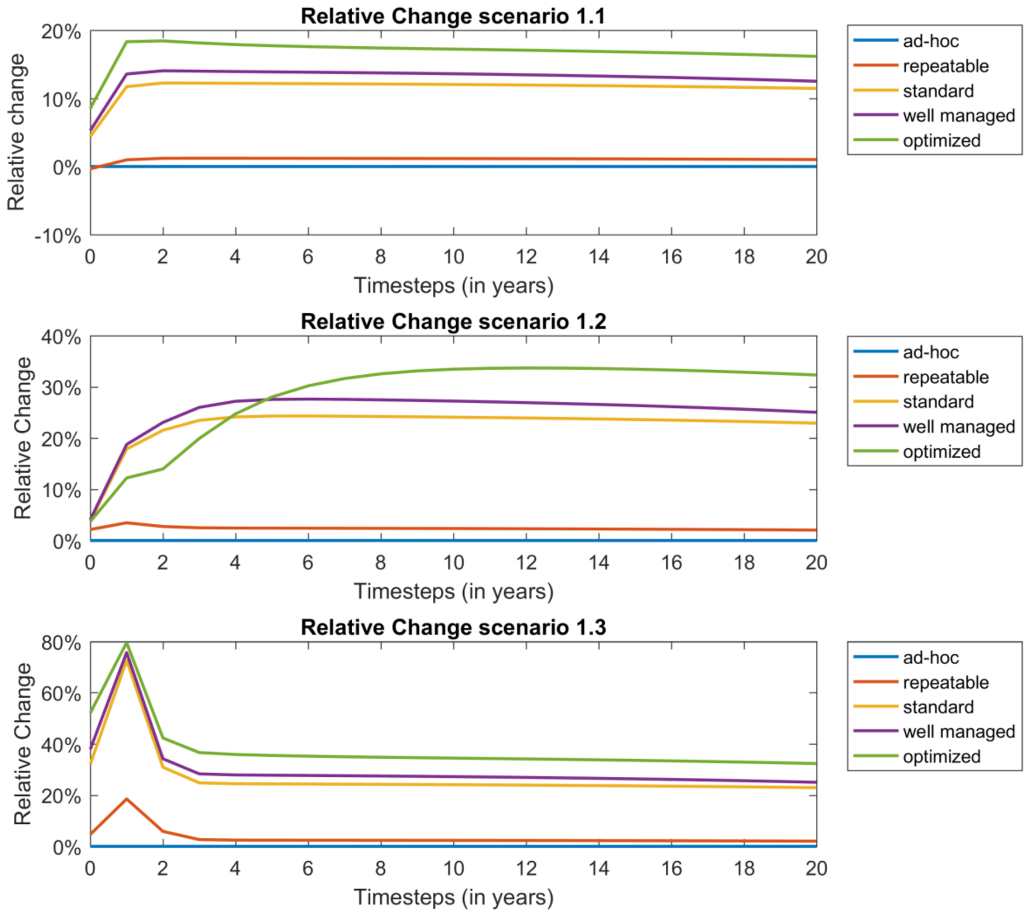


Figure 15 Relative change results of scenario 1. In the y-axis represents the difference between the posterior maturity (ad-hoc until optimized) and the prior maturity (ad-hoc). This graph shows the relative changes in management maturity.

The result is presented as yearly asset costs which are the summation of asset risk, cost of inspection, information management cost, and improvement cost. The model is executed with three different initial grass condition, five different information management maturity level, and three different grass deterioration rates. As can be seen in Figure 14, the cost differs for every maturity level throughout asset lifecycle. The result is shown in Figure 14 and Figure 15, leads to an understanding that the model can recreate the influence of organizational maturity in information management maturity towards the asset expected annual cost. The graph shows that a higher maturity will be beneficial rather than lower maturity organization. This result implies that the organization is suggested to remain constant or increase their scope of management towards the asset. In order to understand the outcome, here are a few explanations and visualization of annual cost at different utility:

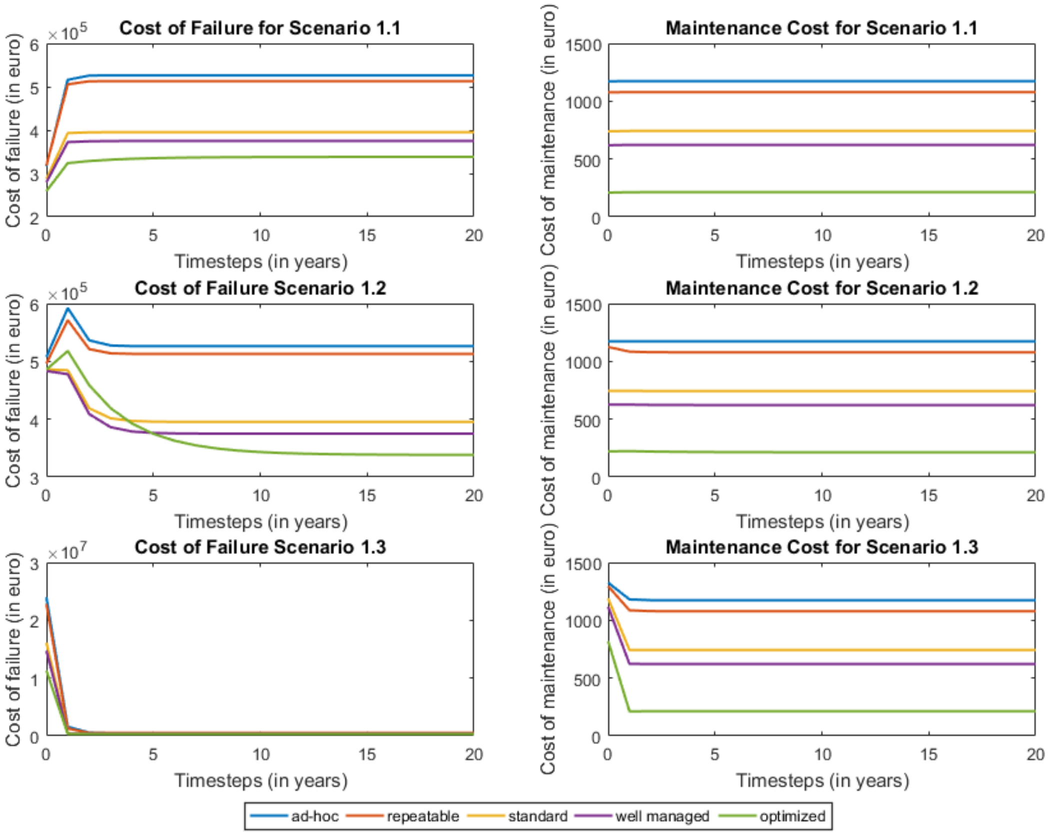


Figure 16 The expected cost of asset maintenance (right column) and cost of failure (left column) during the asset lifecycle

- The expected annual cost of the improvement

The cost of improvement relies on the information quality which is acquired and distributed by the organization during the maintenance lifecycle (see Figure 16 The expected cost of asset maintenance (right column) and cost of failure (left column) during the asset lifecycle. This result implies that the organization with poor management will have the worst information quality. Hence, the organization that has ad-hoc information management tend to intervene superabundantly which led to a higher cost of the improvement. The lack of accuracy in ad-hoc information management causes the organization to misinterpret the condition. On the other hand, a matured organization will tend to have better decision and understanding of the condition. Hence, the cost of the improvement is lower in the poor information management maturity due to the efficiency of intervention.

- Annual Cost of Asset Failure

In Figure 16, graphs presented on the left column shows that the cost of failure at each maturity has the same pattern as the cost of the improvement. An organization with poor management maturity has a higher cost of failure. It is important to notice that the cost of failure has a connection to the asset maintenance work (see Figure 13). The resulting pattern can be explained by understanding the conditional probability matrix of the model. The lower maturity organization has a higher probability of performing maintenance even the asset condition has a good performance. Also, the lower maturity organization can misinterpret the asset condition which leads to overconfidence towards their asset performance. Hence, in the long term, low maturity organization are more likely to misinterpret their asset condition and have a higher probability to desert the asset in a low performance compared to the matured organization. As a result, the cost of failure for ad-hoc information management is higher than the matured organization.

This analysis shows that the interpretation of conditional probability table over the activities are essential. The conditional probability table value should be determined based on a reasonable study to increase the accuracy of the result.

- Asset annual cost in different asset deterioration rate

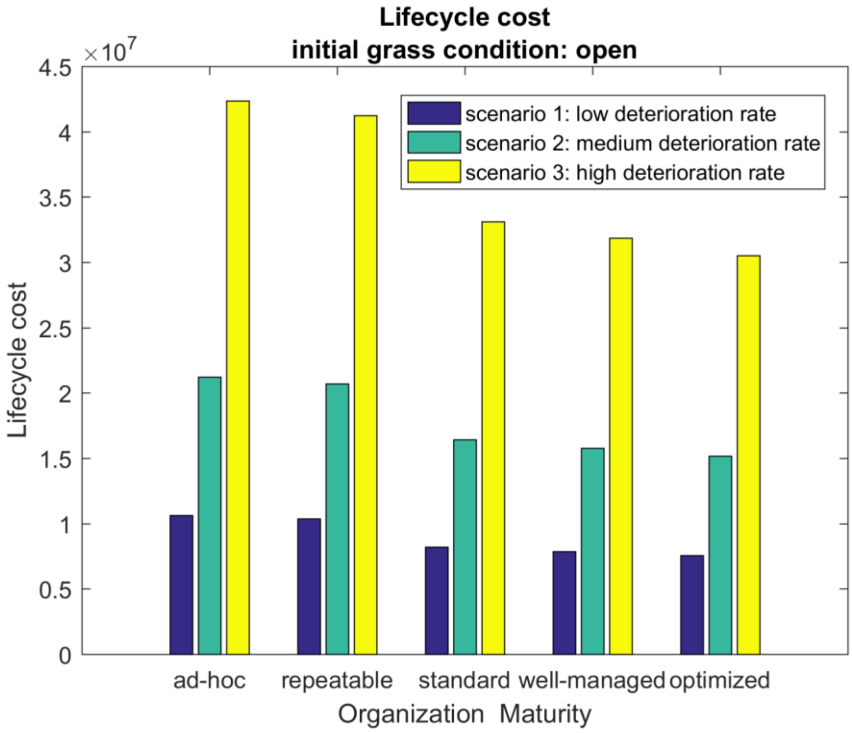


Figure 17 Asset annual cost for scenario 1.2, 2.2 and 3.2. The y-axis shows the annual asset cost which shows an increment as the deterioration rate increase.

The deterioration rate is applied to examine whether how the model will adjust. All of the results are shown in Appendices B. We can identify that all of the results in Figure 17 have relatively the same pattern where lower maturity organization has the highest asset annual cost. A different value is identified where a higher deterioration rate will result in a higher asset annual cost. This outcome is coherent since a higher deterioration will result in a higher frequency of maintenance work and higher risk.

In a nutshell, the annual cost of the asset is dependent with the information management maturity. The extension of the maturity model is promising and can be improved in future research. The results have proven that asset lifecycle cost can be projected based on the organization management maturity and the translation of the case through Dynamic Bayesian Network. This approach can be implemented for different asset scenario. The translation of the case to a Dynamic Bayesian Network, such as the conditional probability table for every activity and the Bayesian Network setup, is an essential process to acquire an adaptable model with a consistent result.

5.2 Value of Information Analysis

The model result can also be presented as a value of information. The value information allows a decision-maker to improve its decision. Based on the result, the annual asset cost is compared at every maturity. This method allows the organization to examine alternatives for improving their information management.

Table 19 shows the value of information between the prior and the posterior information management maturity. If the organization decides to improve their information management maturity, the value of information shows a negative value. This result indicates that the additional information provided is beneficial towards the asset lifecycle. The result indicates it would be not beneficial if the organization maintain or demotes their information management maturity. This result is logical since the lower maturity organization has lower ability to maintain their asset effectively. The result can be dissimilar with different cases.

Table 19 Value of information results

Value of Information for 20 years lifetime (x 10^5 Euro)						
Maturity		Prior Information Management Maturity				
		Ad-hoc	Repeatable	Standard	Well-managed	Optimized
Posterior Information Management Maturity	Ad-hoc	0.0	1.2	10.7	11.9	12.2
	Repeatable	-1.2	0.0	9.4	10.6	11.0
	Standard	-10.7	-9.4	0.0	1.2	1.6
	Well-Managed	-11.9	-10.6	-1.2	0.0	0.4
	Optimized	-12.2	-11.0	-1.6	-0.4	0.0

- (-) the minus sign indicates the value of information is beneficial
- (+) the plus sign indicates the value of information is not beneficial

5.3 Maturity Translations

Management dimension has a broad and complex relationship towards asset lifecycle activities. Almost every activity can correspond to any management dimension. In this research, the translation is done based on capability analysis where activities are broken down into several capabilities that correspond independently to a management dimension. This development enables us to understand different aspect of organizational capabilities that are required to perform certain activities. Based on the capability analysis, the management dimension has interrelation at each activity. At each activity, the management dimension has different significance but not yet been assessed thoroughly in this research. Therefore, for future models with a different case, this approach is required to distinguish the degree of management dimension influence towards an asset lifecycle activity.

6 Conclusion

6.1 General

This research represents an initial attempt to translate the concept of maturity to a project indicator focusing on flood risk asset management. This attempt is set up due to lack of information of the current result of a maturity model. This research attempts to solve by developing a Dynamic Bayesian Network and decision model through a hypothetical case surrounding a flood defenses asset management and information management. The result demonstrates success in acquiring asset indicators at each maturity level and might be useful for discussion to identify an opportunity for improvement. This result might enable an organization to acknowledge the opportunity or loss in different maturity level.

While the application was successful, the determination of a transition or conditional probability value can be improved in future research. It was only through the expert consultation that the value can be determined due to the limitation of this research. The value used in this research is considered to be representative based on the expert consultation. The approach can be improved in the future to acquire more accurate results.

This research noticed that an activity could not be linked to a management dimension independently. An activity may acquire more than a single dimension to accomplish its purpose. We have attempted to linked activity and dimension by using capability. Capability, in this research, is defined as the required capability for an entity to execute a particular activity successfully and it only can relate to a single dimension. This attempt is useful to deeply understand how a management dimension may be involved or have an influence on a particular activity. Other important aspect noticed is the interrelation between the management dimension has a high influence in the attempt of translation to asset performance.

Overall, it is important to note that this maturity model is currently able to provide insight, but this research has shown that it can be more useful where both approaches are applied. This research contributes to the unexplored relation of organization management maturity levels and asset performance. By adopting this extension approach of maturity model, the results can be more representable and useful towards the identification of potential improvements.

6.2 Conclusion towards research questions

6.2.1. Maturity Translations to Case Study

Management dimension has a broad and complex relationship towards asset lifecycle activities. Almost every activity can correspond to any management dimension. In this research, the translation is done based on capability analysis (see chapter 3.2.3) where activities are broken down into several capabilities that correspond independently to a management dimension. This development enables us to understand different aspect of organizational capabilities that are required to perform certain activities. Based on the capability analysis, the management dimension can be weighted, but the approach is still unclear or undefined. Therefore, for future models, this approach is essential to distinguish the degree of management dimension influence towards an asset lifecycle activity.

6.2.2. Translating Organization Management Maturity to Asset Cost and Performance

Asset lifecycle cost and performance rely on the organization decision-making quality. The decision- making the quality of an organization is dependent on the organization management maturity. A method for translating maturity levels to the asset lifecycle cost is the primary objective of this research. We chose to use a semi-hypothetical case on organization decision process towards an asset and translate into a Dynamic Bayesian Network. Dynamic Bayesian Network is chosen because of the probabilistic presence in the organization decision process. This research has shown the possibility of using DBN on translating organization management maturity towards asset lifecycle cost and performance. The results show that the annual asset cost conditional to the organization management maturity can be measured by using Dynamic Bayesian Network, with some remarks on the data that is used.

6.3 Recommendations

There are few recommendations for future research:

1. As mentioned before, the collective influence of IM^3 dimension to a particular activity is one of the main challenges of this research. This challenge implies that IM^3

dimensions are not independent and requires a further approach to know which dimensions are involved in a particular activity. This research has attempted to add another category called capability to understand which IM^3 dimensions are involved in a particular activity. Future research might consider studying on the influence degree of an IM^3 dimension in a particular activity. This insight might help the organization to understand which IM^3 dimension has the most influence and the highest benefit in an improvement.

2. The interrelation of the management dimension is another challenge in this research. It refers to the dependency of each management dimension. This gap of knowledge is not furthered studied in this research, but it is one of the remarks. This insight might change the understanding of IM^3 dimension.

3. The transition and conditional probability values in this research are based on expert consultations. A further study can be done to obtain an accurate probability value at every level of activity performance. A thorough study can eliminate the uncertainty of this current approach.

7 APPENDICES

A Transition and Conditional Probability Matrix

These sections reveal the transition probability matrix used in the DBN simulation. The transition probability matrix is a square matrix used to describe the transition of a Markov chain which is used of the grass deterioration (Table 20) and the conditional probability table of asset activities (Table 21, Table 22Table 23).

Table 20 Grass transition probability matrix set for the simulation

Scenario	Initial Condition	Transition Probability at t+1		
		Closed	Open	Fragmented
1	1.1 Closed	0,99	0,025	0,005
	1.2 Open	0	0,99	0,03
	1.3 Fragmented	0	0	1
2	2.1 Closed	0,98	0,01	0,01
	2.2 Open	0	0,98	0,02
	2.3 Fragmented	0	0	1
3	3.1 Closed	0,96	0,02	0,02
	3.2 Open	0	0,96	0,04
	3.3 Fragmented	0	0	1

Table 21 Data management conditional probability table set for the simulation

Data Management Ability		Lack of Data Management			Accessible			Accessible and Georeferenced			Advanced Information and Centrally Available			Optimized		
Information Acquired from Inspection		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
Accessible Information	Closed	0.6	0.2	0.2	0.7	0.15	0.15	0.8	0.1	0.1	0.9	0.05	0	1	0	0
	Open	0.2	0.6	0.2	0.15	0.7	0.15	0.1	0.8	0.1	0.05	0.9	0.1	0	1	0
	Fragmented	0.2	0.2	0.6	0.15	0.15	0.7	0.1	0.1	0.8	0.05	0.05	0.9	0	0	1
C= Closed ; O= Open; F=Fragmented																

Table 22 Conditional probability table matrix in the acquiring information activity set for the simulation

Organization inspection ability		Free Will Inspection			Poor Inspection			Planned Inspection			Advanced Inspection			Optimized		
Grass Condition State		C	O	F	C	O	F	C	O	F	C	O	F	C	O	F
Acquired Information	Closed	0.34	0.33	0.33	0.5	0.25	0.25	0.75	0.12	0.12	0.95	0.05	0	1	0	0
	Open	0.33	0.34	0.33	0.25	0.5	0.25	0.13	0.75	0.13	0.03	0.95	0.02	0	1	0
	Fragmented	0.33	0.33	0.34	0.25	0.25	0.5	0.12	0.13	0.75	0	0.05	0.95	0	0	1
C= Closed ; O= Open; F=Fragmented																

Table 23 Conditional probability table matrix set for the simulation

Grass Condition State		C	O	F
Maintenance Decision	Improved	0	0	1
	Nothing	1	1	0
C= Closed ; O= Open; F=Fragmented				

B Model Results

The DBN model is simulated by using the GeNie Modeler programme. The model is simulated with three different scenarios, three different initial conditions, and five different maturities. The result is presented in the expected annual cost (see Figure 18, Figure 19 and Figure 20), the expected maintenance cost and the expected cost of failure (see Figure 21, Figure 22, and Figure 23).

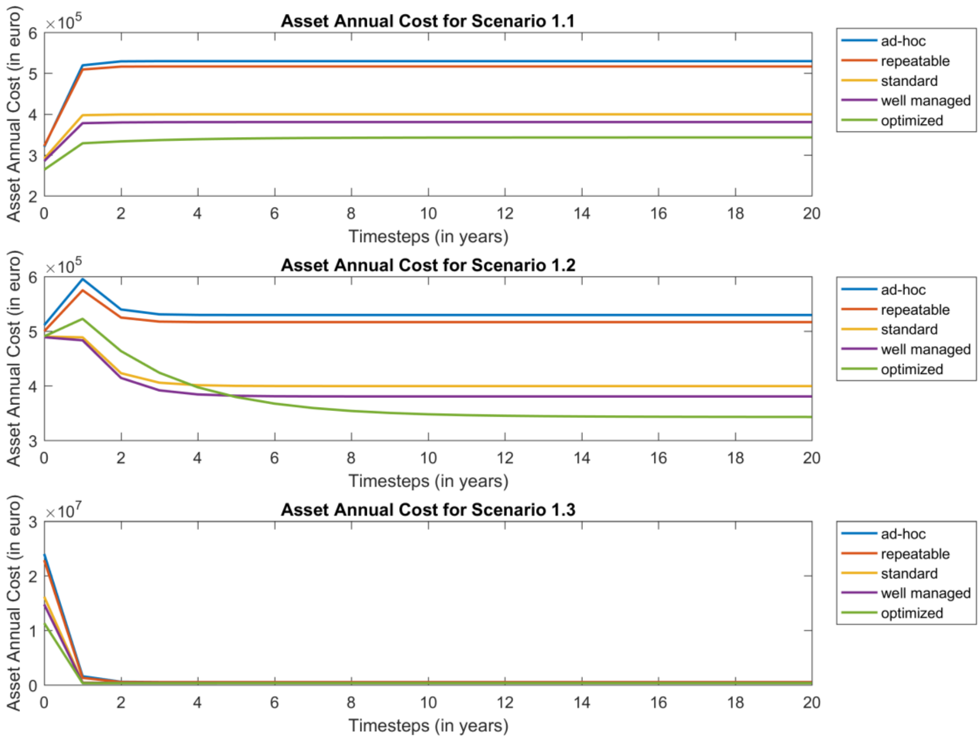


Figure 18 The expected asset annual cost for scenario 1

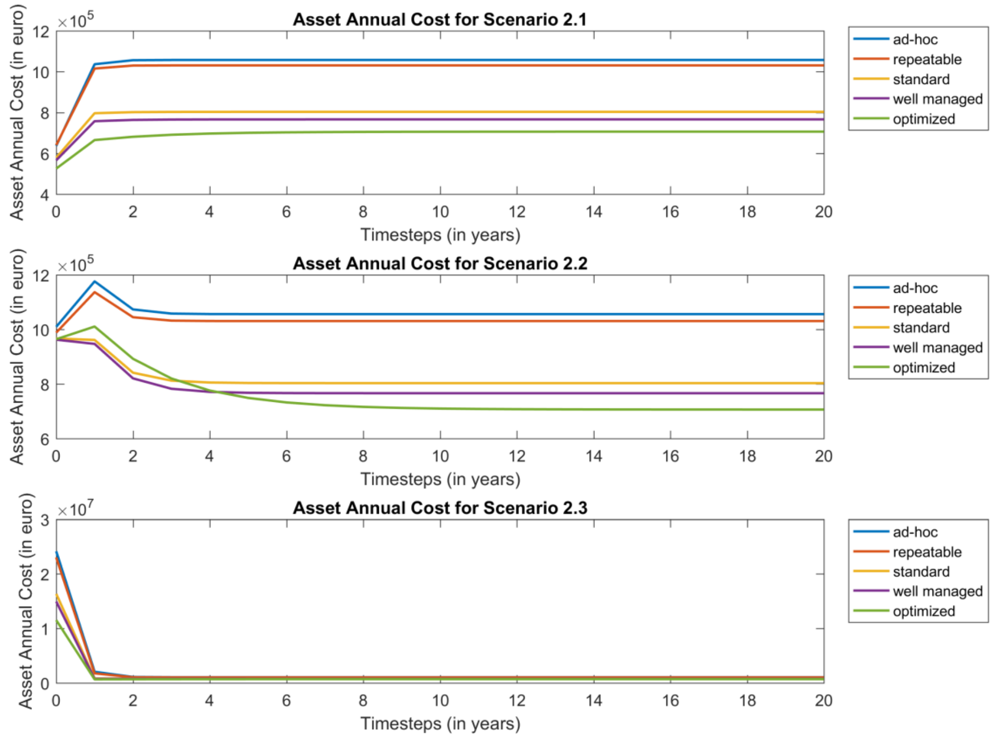


Figure 19 The expected asset annual cost for scenario 2

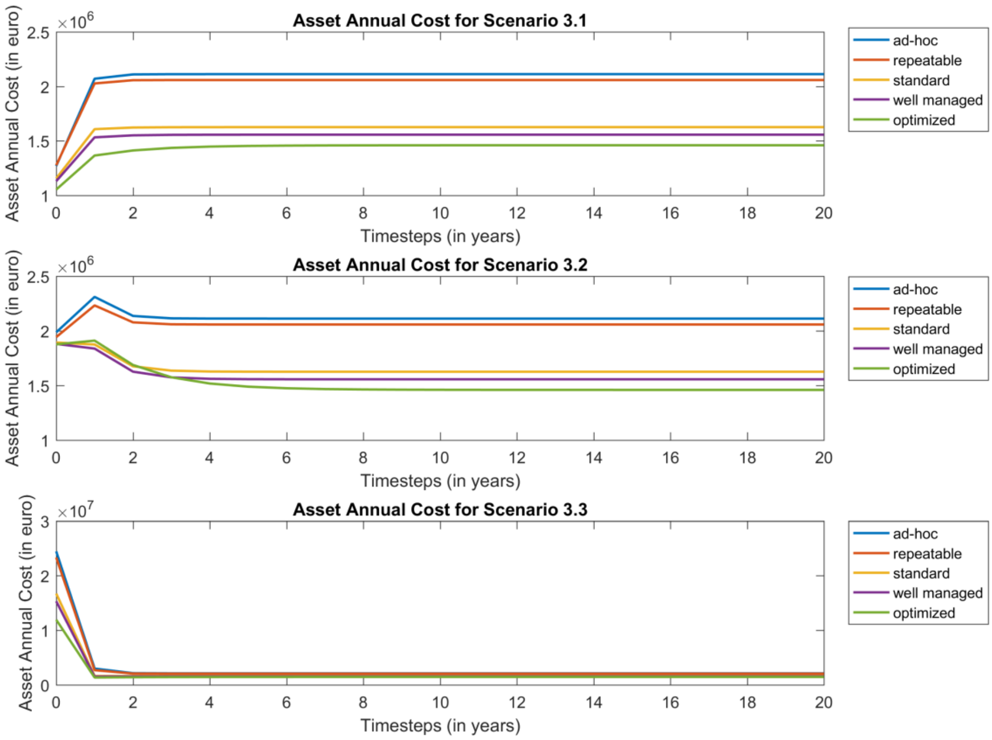


Figure 20 The expected asset annual cost for scenario 3

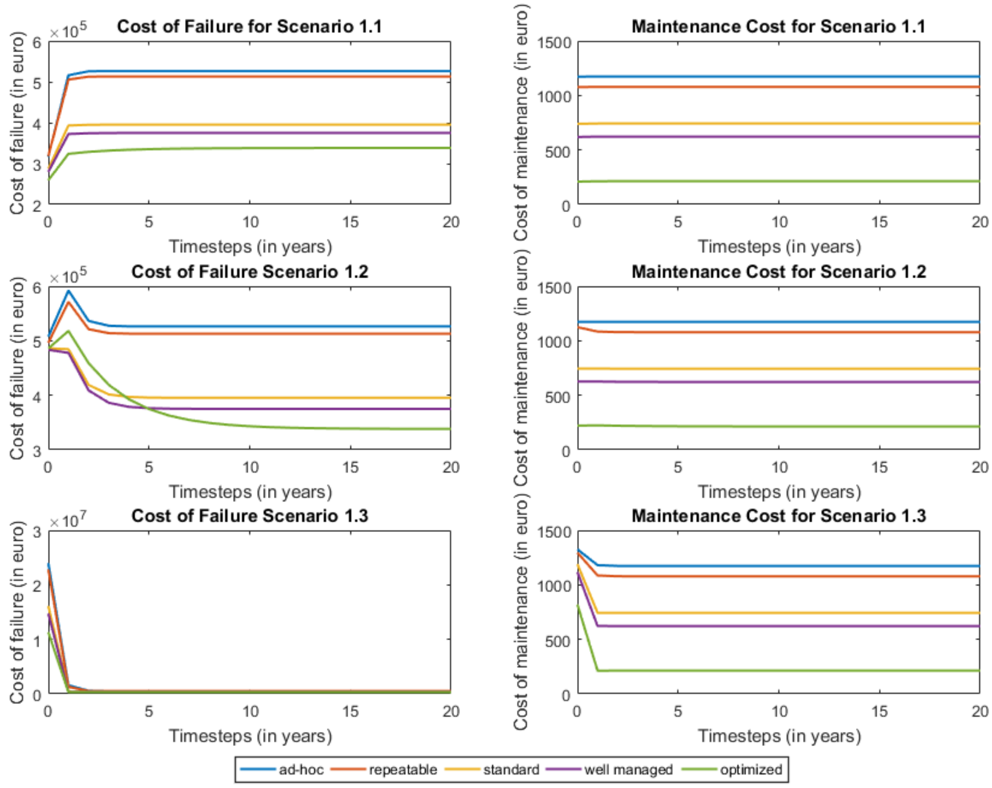


Figure 21 The expected cost of maintenance and failure for scenario 1

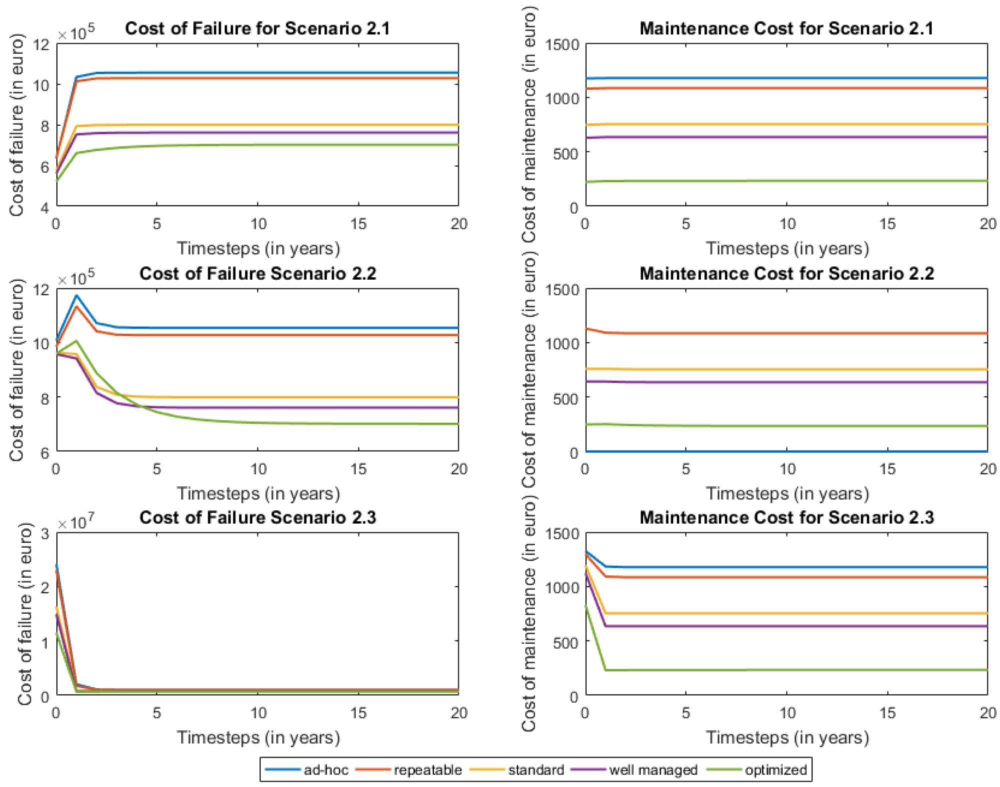


Figure 22 The expected cost of maintenance and failure for scenario 2

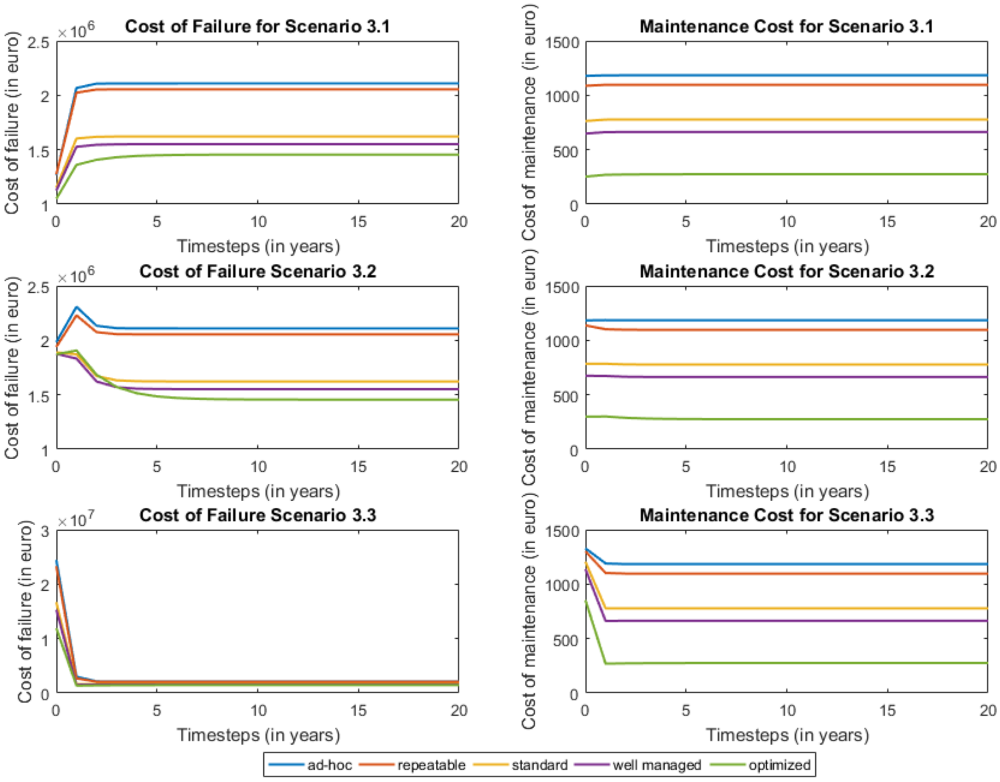


Figure 23 The expected cost of maintenance and failure for scenario 3

8 Bibliography

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Buijs, F. A., Hall, J. W., Sayers, P. B., & Van Gelder, P. H. A. J. M. (2009). Time-dependent reliability analysis of flood defences. *Reliability Engineering and System Safety*, *94*(12), 1942–1953. https://doi.org/10.1016/j.ress.2009.06.012

Commission of the European Communities. (2004). *Communication from The Commission to The Council, The European Parliament, The European Economic and Social Committee and The Committee of The Regions*.

European Regional Development Fund. (2015). *The FAIR Project*.

Foster, P., & Hoult, S. (2013). The Safety Journey: Using a Safety Maturity Model for Safety Planning and Assurance in the UK Coal Mining Industry. *Minerals*, *3*(1), 59–72. https://doi.org/10.3390/min3010059

Frangopol, D. M., Kallen, M.-J., & Noortwijk, J. M. van. (2004). Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. *Progress in Structural Engineering and Materials*, *6*(4), 197–212. https://doi.org/10.1002/pse.180

GFMAM. (2015). Asset Management Maturity - A Position Statement, (October).

Giglio, J. M., Friar, J. H., & Crittenden, W. F. (2018). Integrating lifecycle asset management in the public sector. *Business Horizons*, *61*(4), 511–519. https://doi.org/10.1016/j.bushor.2018.03.005

Halfawy, M. (2008). Integration of Municipal Infrastructure Asset Management Process:Challenges and Solutions. *Journal of Computing in Civil Engineering*, *22*(2), 114–122. https://doi.org/10.1061/(ASCE)0887-3801(2008)22

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Hansson, S. O. (2005). Decision Theory. *Technology*, *19*(1), 1–94. https://doi.org/http://www.infra.kth.se/~soh/decisiontheory.pdf

Hastings, N. A. J. (2014). *Physical Asset Management Handbook.*

Howard, R. (1962). Information Value Theory, (1).

Humphrey, W. S. (1987). Characterizing the Software Process: A Maturity Framework. Techn. Rept, (CMU/SEI-87-TR-11), 73–79.

IAM. (2012). Asset Management – an anatomy Asset Management – an anatomy, (February), 1–63.

Introna, V., Cesarotti, V., Benedetti, M., Biagiotti, S., & Rotunno, R. (2014). Energy Management Maturity Model: An organizational tool to foster the continuous reduction of energy consumption in companies. *Journal of Cleaner Production, 83,* 108–117. https://doi.org/10.1016/j.jclepro.2014.07.001

Jonkman, S. N., Schweckendiek, T., Jorissen, R. E., & van den Bos, J. P. (2017). Flood Defences, 141.

Jonkman, S. N., Voortman, H. G., Klerk, W. J., & van Vuren, S. (2018). Developments in the management of flood defences and hydraulic infrastructure in the Netherlands. *Structure and Infrastructure Engineering*, *14*(7), 895–910. https://doi.org/10.1080/15732479.2018.1441317

Kallen, M.-J. (2007). Markov processes for maintenance optimization of civil infrastructure in the Netherlands. Retrieved from http://medcontent.metapress.com/index/A65RM03P4874243N.pdf%5Cnhttp://www.narcis.nl/publication/RecordID/oai:tudelft.nl:uuid:2eac935e-cdb1-4c0c-92d1-cbcc8dd2d867

Kind, J. M. (2014). Economically efficient flood protection standards for the Netherlands.

Journal of Flood Risk Management, *7*(2), 103–117. https://doi.org/10.1111/jfr3.12026

Klerk, W., Heijer, F., & Schweckendiek, T. (2015). Value of information in life cycle management of flood defences. *Safety and Reliability of Complex Engineered Systems*, (October), 931–938. https://doi.org/10.1201/b19094-125

Klerk, W. J., Roscoe, K. L., Tijssen, A., Nicolai, R. P., Sap, J., & Schins, F. (2018). Risk based inspection of flood defence dams : an application to grass revetments. *IALCCE2018 (Submitted)*.

Kuijper, B., & Kallen, M. J. (2012). Uncertainty in optimal decisions for dike maintenance. *Structure and Infrastructure Engineering*, *8*(4), 317–327. https://doi.org/10.1080/15732479.2011.563086

Lawrence, D. B. (1999). *The Economic Value of Information* (1st Editio). Des Moines: Springer.

Lazanyi, I., & Horvath, G. (1997). Deterioration of flood protection dikes due to shrinkage cracking Pathologie des digues k cause de fissures de retrait. *International Society for Soil Mechanics and Geotechnical Engineering*.

Le Bars, D., Drijfhout, S., & De Vries, H. (2017). A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. *Environmental Research Letters*, *12*(4). https://doi.org/10.1088/1748-9326/aa6512

Marchese, D. C., Bates, M. E., Keisler, J. M., Alcaraz, M. L., Linkov, I., & Olivetti, E. A. (2018). Value of information analysis for life cycle assessment : Uncertain emissions in the green manufacturing of electronic tablets. *Journal of Cleaner Production, 197*, 1540–1545. https://doi.org/10.1016/j.jclepro.2018.06.113

McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, *662*(1), 47–52. https://doi.org/10.1177/0956247807076960

Mettler, T. (2011). Maturity assessment models: a design science research approach. *International Journal of Society Systems Science*, *3*(1/2), 81.

https://doi.org/10.1504/IJSSS.2011.038934

Micevski, T., Kuczera, G., & Coombes, P. (2002). Markov Model for Storm Water Pipe Deterioration. *Journal of Infrastructure Systems, 8*(June), 49–56. https://doi.org/10.1061/(ASCE)1076-0342(2002)8:2(49)

Milajlovic, V., & Petkovic, M. (2001). Dynamic Bayesian Network: a State of the Art. *University of Twente*.

Parlikad, A. K., & Jafari, M. (2016). Challenges in infrastructure asset management. *IFAC-PapersOnLine*, *49*(28), 185–190. https://doi.org/10.1016/j.ifacol.2016.11.032

Postek, K., den Hertog, D., Kind, J., & Pustjens, C. (2018). Adjustable robust strategies for flood protection. *Omega (United Kingdom)*, (September). https://doi.org/10.1016/j.omega.2017.12.009

Rijke, J., & Marcel, H. (2014). *Inventarisatie beheer- en onderhoudskosten primaire waterkeringen Basisgegevens voor LCC binnen het HWBP*. Utrecht.

Rijkswaterstaat. (2017). Schematiseringshandleiding grasbekleding, (december 2016).

Rinsum, G. P. Van. (2018). Grass revetment reinforcements.

Schanze, J., Zeman, E., & Marsalek, J. (2011). *Flood Risk Management: Hazards, Vulnerability, and Mitigation Measures*. Ostrov: Springer. https://doi.org/10.1017/CBO9781107415324.004

Scutari, M., & Strimmer, K. (2011). Introduction to Graphical Modelling. *Handbook of Statistical Systems Biology*, (May), 235–254. https://doi.org/10.1002/9781119970606.ch11

Straub, D. (2014). Value of information analysis with structural reliability methods. *Structural Safety*, *49*, 75–85. https://doi.org/10.1016/j.strusafe.2013.08.006

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T., & De Vriend, H. J. (2013). Ecosystem-based coastal defence in the face of global change. *Nature, 504*(7478), 79–83. https://doi.org/10.1038/nature12859

Thorne, C. R., Lawson, E. C., Ozawa, C., Hamlin, S. L., & Smith, L. A. (2018). Overcoming uncertainty and barriers to adoption of Blue-Green Infrastructure for urban flood risk management. *Journal of Flood Risk Management*, *11*, S960–S972. https://doi.org/10.1111/jfr3.12218

Tourment, R., Beullac, B., & Poulain, D. (2017). Structures for Flood Defense and Management. *Floods*, 193–208. https://doi.org/10.1016/B978-1-78548-268-7.50011-0

Vlad, D. (2017). *Primary Flood Defenses in the North Sea Region Governance Barriers to Proactive Asset Management Implementation*. *Utrecht University*.

Volker, L., Ligtvoet, A., Boomen, M. Van den, Wessels, L. P., Velde, J. Van der, Lei, T. E. Van der, & Herder, P. M. (2013). Asset management maturity in public infrastructure: the case of Rijkswaterstaat. *International Journal of Strategic Engineering Asset Management*, *1*(4), 439. https://doi.org/10.1504/IJSEAM.2013.060469

Volker, L., Van Der Lei, T., & Ligtvoet, A. (2011). Developing a maturity model for infrastructural asset management systems. *Conference on Applied Infrastructure Research*, 7–8.

Vrijling, J. K., & Verlaan, J. G. (2015). Financial Engineering.

Williams, K., Robertson, N., & Haritonov, C. R. (2003). Reliability Capability Evaluation and Improvement Strategies For Subsea Equipment Suppliers, 165–173.