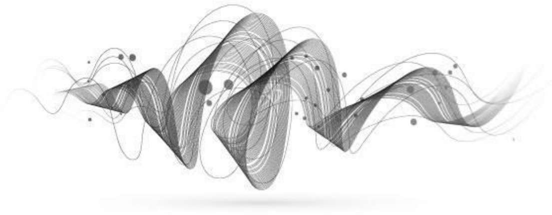
Long-term planning of large interventions within complex and dynamic infrastructure systems

Introducing a decision-support method for strategic intervention planning



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DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS REPORT – WOUTER JASPERS 4387473 & MARK HAVELAAR 4419294

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COLOPHON

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FOREWORD

This report is the result of our graduation research for the completion of the master Construction Management and Engineering at the Delft University of Technology. It introduces a decision-support approach within the field of Infrastructure Asset Management. This approach is able to assess the dynamic complexity and uncertainty subjected to the long-term planning of large interventions, for infrastructure asset systems.

Both of us were interested in this subject before the start of this thesis. The lectures in infrastructure asset management, and both our working experience within the field, is the basis for our interest. We both wanted to investigate the influences of long-term uncertainties on infrastructure asset management. This is grounded by the fact that infrastructure assets are designed for such long lifecycles, and performance of these assets in the changing environments becomes more, and more important.

After starting the thesis project individually, our graduation thesis committee suggested that it could be better to collaborate in one master thesis project. This due to the complexity of the case, and for handling a much larger case than could be performed individually. Moreover, with this collaboration we could both act as a real asset manager for our individual asset system (Mark: Road, Wouter: Lock). We have been working together for a lot of years, during our bachelor and master study. Therefore, a collaborative master thesis project was no problem for both of us, and has been of additional value for this study.

We would like to make use of this foreword by thanking the members of our graduation committee, for their input, knowledge, time and new perspectives which have been of great value for this master thesis. Special thanks go to Willem Auping, who has enabled us to gain the skills, and knowledge for applying a method which was totally new for both of us. Due to his supervision, we were able to develop the programming, and modelling skills for properly conducting this research. Furthermore, we want to thank the interviewees who found the time for providing important input for our thesis, and being critical about their working field.

Finally, because this is a dual thesis, we both want to spend a few words individually;

Mark:
First of all , I would like to thank Wouter, for being an excellent graduation partner. Second, I would like to thank my supervisor at Antea Group, Eric Waltje, for his support, and help in the graduation process and getting contacts for information, and interviews. Furthermore, I would like to thank my colleagues at Antea Group, which were always available for reviewing, or discussing my thesis, or just have a talk about a different subject. Finally, I would like to thank my family, friends, and of course my girlfriend, Melanie, for their trust, support, review, and years of patience.

Wouter:
First, I want to thank my graduation partner Mark for his hard work and dedication to this study. Second, I want to thank my colleagues at BAM, and especially my supervisor Jaap van den Elshout, for their support during this graduation process. Third, I want to thank my family and friends for stimulating me to pursue the track that has led me to this point in my life. Thank you for your support in good times and in bad times. Finally, I want to thank my girlfriend Bianca, for her love, trust, patience and unconditional support. I greatly acknowledge that I could not have done this without you all.

We hope you will enjoy reading the report, and that you will not be reluctant to get in contact for any questions or discussion about the thesis.

Mark Havelaar & Wouter Jaspers
Delft, 13 October 2017

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EXECUTIVE SUMMARY

Goal and scope of the study

This study analyses the contributions of a multivariate simulation approach within the long-term planning of large interventions decisions in infrastructure asset management. During this study, the combination of the Exploratory System Dynamics Modelling and Analysis (ESDMA) and the adaptation pathways approach is used as multivariate simulation approach. With this approach an adaptive long-term planning was developed for a network of complex multifunctional infrastructure asset systems, subjected to dynamic uncertainty. Specifically, within the long-term planning, large interventions were initiated to ensure the technical and functional performance of a multifunctional lock and road system. The lock system schematically represented the lock complex of IJmuiden. The road system represented the road network around Amsterdam. These systems were connected through the city of Amsterdam with its harbour, local economy, rail system, canal system, and a limited amount of area.

Cities as Amsterdam are rapidly transforming, and their infrastructure networks are not always resilient for these future developments. On a global scale, cities are growing into megacities, whilst counter urbanisation causes significant population declines. To adapt to these future developments, infrastructure asset management is applied. Within infrastructure asset management, asset managers apply a long-term planning for large interventions to maximise the performance of their infrastructure asset systems. Insight is required in the uncertain future developments subjected to the infrastructure asset systems, to strategically apply a long-term planning. These uncertainties can change dynamically over time, and can result from developments in population, economy, innovation, climate, and land use. Moreover, infrastructure asset systems are complex systems. They can perform multiple functions on different scales, and influence each other due to their local proximity, or dependencies.

The adaptive long-term planning developed during this study included a set of robust interventions for the interconnected lock of IJmuiden and road network of Amsterdam. These interventions incorporated their primary (transportation) and secondary (flood protection, sewer drainage) function. The systems were subjected to dynamic uncertain developments.

Within the set of interventions for the road system, it was found that the ring road around Amsterdam (A10) will require additional road lanes on a short basis. These additional road lanes have to be added during the renovation project that is currently being applied. The early adding of road lanes, is the only robust (first) intervention that can suffice in scenarios with high urbanisation and macro-economic growth. In this high scenario, additional road lanes have to be constructed at a later stage. This is also the case for medium urbanisation and macro-economic growth scenarios. In low urbanisation and macro-economic growth scenarios, no additional interventions are required. Innovations as automatic driving and ITS showed to be of great importance to ensure sufficient road capacity in hard scenarios.

The road network is dependent on its underlying sewer for rain water drainage. The capacity of this sewer will need to be enlarged if climate change increases precipitation peak intensities. The road lanes that have to be constructed during the first intervention moment have a design horizon of 100 years. Since the intervention for the sewer system falls within this time horizon for all climate scenarios, it is advised to adjust the sewer capacity during the construction of the first additional road lanes. This avoids unnecessary (double) interventions.

Within the set of interventions for the lock system, it was found that the current biggest lock at IJmuiden (the Noordersluis) has to be renovated on a short basis. The renovation has to be initiated after overcapacity is created by the new sea lock of IJmuiden. This new sea lock is expected to open in 2019. Depending on climate change and innovation scenarios the Noordersluis will reach its end technical lifetime between 2027-2036. If the renovation is initiated after this technical lifetime is reached, the renovation will cause large waiting times. In a later stage an additional new sea lock will have to be constructed according to the future that unfolds. In a high macro-economic growth scenario an additional 'innovative lock' is required. With high economic growth, traffic intensities are high, and innovations have to be extensive. These innovations can reduce the time needed for lock cycles, and increase the locks capacity. This capacity is needed for the high traffic intensities. In low and medium macro-economic growth scenario's a replication of the new sea lock at IJmuiden will suffice.

The lock system of IJmuiden is an important flood control structure in the Netherlands. The required retaining height can change dependent on climate change scenarios. The first required intervention moment for the retaining height is shortly after the additional lock is constructed during the second intervention moment. It is advised to adjust the retaining height after construction of this lock is completed. All machinery and equipment will still be at the construction site, which leads to a higher economic viability.

The development of these long-term plans, involved the assessment of dynamic complexity and uncertainty. In current asset management practices, long term plans are predominantly based on static decision support methods, which only consider single-sector infrastructures. Dynamic complexity and uncertainty subjected to the infrastructure systems is neglected. However, dynamic complexity and uncertainty can affect the performance of an infrastructure asset system. Maximising the performance of an infrastructure system is the main aim of asset management. A decision-support method, able to incorporate all relevant dynamically changing complexity and uncertainty is necessary.

Building on this necessity, the following research question has been formulated:

Research Question:	*"What can the combination of the ESDMA and adaptation pathways approach contribute to the long term planning of large intervention decisions for complex infrastructure asset systems subjected to dynamic uncertainty?"*

To assess the research question, the following hypothesis has been formulated:

Hypothesis:	*"The long-term planning of large intervention decisions can be improved by enabling the assessment of dynamic complexity and uncertainty with the combination of the ESDMA and the adaptation pathways approach."*

Methodology

This study applies the ESDMA and adaptation pathways approach since they are complementary to one another, and can assess dynamic complexity and uncertainty. The ESDMA approach can support the adaptation pathways approach by addressing the dynamic uncertainty and complexity subjected to infrastructure asset systems. Within ESDMA, Exploratory Modelling and Analysis (EMA) is applied, which is able to address the uncertainty subjected to infrastructure asset systems. Furthermore, a System Dynamics (SD) model is used to address the dynamic complexity of infrastructure asset systems. The ESDMA results are incorporated into adaptation pathways with the adaptation pathways approach.

First, an assessment was made of the current practices within the long-term planning of large intervention decisions in infrastructure asset management. These practices frame the main challenges within this field. Second, the combination of the ESDMA and adaptation pathways approach was applied to a case study. In order to do so, a SD model was built which represented the city, harbour, lock, road, the local economy, and the city area. The computational model was subjected to uncertain future developments, resulting from changes in climate, innovation, population, economy, and land use. The uncertain developments were summarised into a set of scenario packages. The scenario packages were used to form a robust set of intervention policies per plausible package of future developments (low, medium, and hard). Third, the results of the followed approach were translated to the main challenges found in the current practices of infrastructure asset management.

Results

The main challenges within the long-term planning of large intervention decisions were the incorporation of dynamic complexity and uncertainty. The first assessed aspect of complexity was the influence between interconnected infrastructure systems due to their local proximity, or dependencies on one another. It was found that decision-makers within infrastructure asset management rarely develop a shared policy in which all relevant stakeholders from different infrastructure systems are incorporated. It is perceived as challenging to translate the effects of an intervention from a network to operational level, with so many variables and underlying relations involved. This leads to the misinterpretation of the effects of an intervention, and thereby creates insufficient performance of asset systems.

The proposed approach assessed the interconnection between infrastructure asset systems. Interventions were implemented on a network level, and the effects that these interventions had on other asset systems and sectors were measured on an operational level.

It was observed that an intervention on the lock system, increased or decreased the amount of tonnage distributed in the harbour. This change in harbour distribution affected the traffic intensity on the interconnected road system. The required magnitude and/or timing of an intervention for the road system shifted. This influence was observed in the opposite direction as well (from road to lock). Insight was created in the influence between infrastructure systems with direct interfaces, and infrastructure systems that indirectly influenced one another through other systems. The effects of an intervention could be interpreted dynamically over time, and subsequent interventions were implemented accordingly to assure maximum asset performance.

The second assessed aspect of complexity, was the multifunctional performance of the infrastructure systems. In current asset management practices interventions have to incorporate the technical and functional lifetime, for multiple functions at the same time. This involves the assessment of many variables and their underlying relations. Asset managers perceive it as challenging to incorporate all these variables and underlying relations with the available static decision support tools. Especially, when taking uncertain future developments into consideration, which affect the technical and functional lifetime for all functions. Therefore, interventions are not always based on both the technical and functional performance for all relevant functions. However, the functional lifetime of the asset can be shorter than its technical lifetime (or vice versa). Furthermore, the secondary function of an asset can require an intervention sooner than the primary function. This can lead to unnecessary interventions, which induce more costs, create negative side effects, and can influence the infrastructures performance.

With the proposed approach, the technical and functional performance of the lock and road system was predicted, under every possible future scenario. This was done for both the primary (transportation) and the secondary (flood protection, sewer drainage) function. Interventions for both functions were combined during the same intervention moment, to increase the economic viability of the long-term planning. An intervention for the lock retaining height was combined with the construction of a second new sea lock. Furthermore, the sewage capacity was enlarged during the construction of the first additional road lanes.

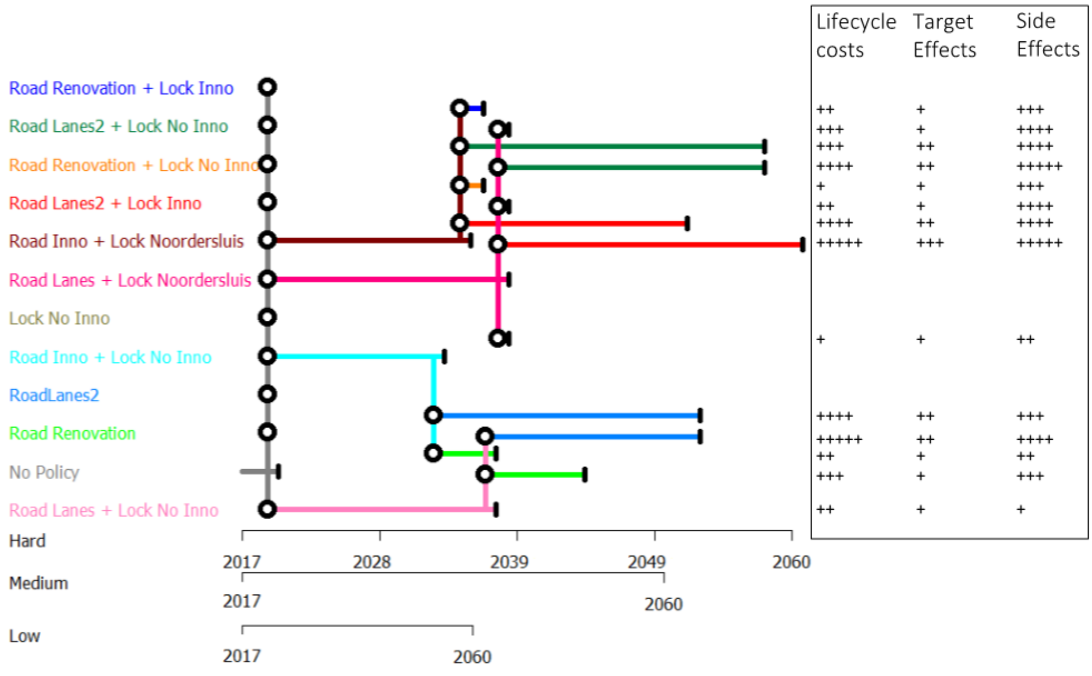
In real world practices there is a fair chance that these interventions would not have been combined. In the Netherlands, 85% of the government bodies agree that climate change will have severe consequences, but only half of the government bodies takes climate change into consideration. The interventions for the lock retaining height and the sewage capacity were mainly dependent on developments in climate change. If climate change would not have been taken into consideration, the opportunity to combine the interventions would have been neglected. An extra intervention would be required in later stage to adjust the lock retaining height. Moreover, the road would have to be opened (before its end technical lifetime) to adjust the sewage capacity.

When considering the dynamic uncertainty subjected to the complex infrastructure systems, asset managers perceive it as challenging to gain insight in the magnitude and time of occurrence of future developments. To cope with this uncertainty, asset managers often overestimate future developments, by applying large bandwidths or solely designing for the worst case. Thereby, interventions are often overdesigned, which can lead to unnecessary costs.

The proposed approach assessed the dynamic uncertainty, subjected to the complex infrastructure systems. The technical and functional performance of the infrastructure systems in both their primary and secondary function was measured dynamically over time when subjected to dynamic uncertainty. With the use of key performance indicators the main influences on the primary transportation function of both the lock and the road were obtained. The functional performance was mainly affected by developments that directly influenced the traffic intensities (developments in macro-economy, city population, labour population, and innovation). Moreover, the functional performance was affected by the technical performance, which was mainly dependent on developments that influenced the deterioration and the technical lifetime of the infrastructure systems (developments in innovation and climate change). The technical and functional performance of the secondary function of both infrastructure systems was mainly dependent on developments in climate change. The higher the climate change scenario, the earlier interventions were required.

By gaining insight in the magnitude and time of occurrence of future developments, interventions were adjusted to the required performance of the road and lock system. Strategic ‘no regret’ decisions were identified to be taken in the short-term, and a framework was established to guide actions in the future. A ‘no regret’ decision is an intervention which has to be applied in all future scenarios, on the basis of costs, target effects and side effects. Figure 1 presents this framework in the form of an combined adaptation pathways map.

The figure is scaled on the hard scenario, the time scales for the medium and low scenario are adjusted to this scaling. In the short-term the Noordersluis has to be renovated *(Lock Noordersluis)* and additional road lanes have to be added to the A10 *(Road Lanes)*. Depending on the future that unfolds, additional road lanes have to be constructed again *(Road Lanes2)*, and either an 'innovative' *(Lock Inno)* or 'non-innovative' lock *(Lock No Inno)* has to be built. To ensure maximum asset performance, the future developments with the highest impact on the performance of the infrastructure asset systems can be monitored in the real world. The framework can thereby be adapted to new experiences and insights.



Map generated with Dynamic Pathways Generator, ©2015, Deltares, Carthago Consultancy

Figure 1. Combined adaptation pathways map of intervention policies including scorecard
On the left, the combination of intervention policies (appendix C) are listed. Each combination of intervention policies has certain lifecycle costs, target effects, and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The more '+' marks, the more lifecycle costs, the better the target effects (increasing asset performance), and the more negative side effects (hindrance, pollution etc.) are attached to the intervention policies. At the bottom, the time scale is presented for the hard, medium, and low scenario.

Conclusion

The proposed approach can contribute to the long-term planning of rapidly transforming cities, as can be the case for the city of Amsterdam and its infrastructure network. Dynamic uncertainty and complexity can be assessed. The technical and functional performance of its complex infrastructure systems can be predicted under every possible future scenario. This can be done for both their primary and the secondary functions. The magnitude and timing of interventions can be identified, and adjusted to the required performance. The effects that interconnected infrastructure systems have on one another can be identified and taken into consideration. Switches between strategies can be made according to the future developments that unfold, and opportunities that are identified. Costs, time and negative side effects can be minimized. The target effects (performance) of the infrastructure systems can be maximized to create maximum value. All this can be performed on a more substantial and informed basis.

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LIST OF ABBREVIATIONS

ABP	Assumption Based Planning
AD	Automated Driving
CBA	Cost Benefit Analysis
CLD	Causal Loop Diagram
DAPP	Dynamic Adaptive Policy Pathways
DISK	Data Informatie Systeem Kunstwerken (Data Information System Civil Structures)
EMA	Exploratory Modelling and Analysis
ESDMA	Exploratory System Dynamics Modelling and Analysis
FLSA	Functional Lifetime Scenario Analysis
FMECA	Failure Mode, Effects ,and Criticality Analysis
I/C	Intensity/Capacity
ITS	Intelligent Transportation Systems
KPI	Key Performance Indicator
LEAB	Laag Energie Asfalt Beton (Low Energy Asphalt Concrete)
LCC	Life Cycle Costing
MTPA	Million Tons Per Annum
MVT	MotorVoerTuigen (Motor Vehicles)
NAP	Normaal Amsterdams Peil (Reference Water Level Amsterdam)
NPV	Net Present Value
PCE	Person Car Equivalent
PROBO	PRObabilistisch Beheer en Onderhoud (Risk based Operations and Maintenance)
RCM	Reliability Centred Maintenance
RDM	Robust Decision Making
RINK	Risico Inventarisatie Natte Kunstwerken (Risk Inventory of Hydraulic Structures)
SD	System Dynamics
TOM	Trade Off Matrix
WLO	Welvaart en LeefOmgeving (Prosperity and Environment)

NOMENCLATURE

- **Asset manager**

  Owner of the assets, responsible for the asset management activities (Velde & Hooimeijer, 2010).

- **Dynamic uncertainty**

  Limited knowledge about continually changing future, past, or current events (Walker, Lempert, & Kwakkel, 2013)

- **Dynamic complexity**

  Continually changing non-simple relations between the elements within and between systems (Ridder, 2016)

- **Functional lifetime**

  The total time for which the asset is able to meet its functional performance requirements (Rijkswaterstaat, 2015c)

- **Infrastructure**

  The system of public works of a country, state, or region ("Infrastructure," 2017). More specifically this can be roads, locks, harbours or sewers.

- **Infrastructure asset system**

  An infrastructure item, thing or entity that has potential or actual value to an organisation (Hastings, 2014). More specifically this can be road, lock, harbour or sewer systems.

- **Infrastructure asset management**

  A coordinated activity of an organisation to realise value from infrastructure assets on the basis of current data, and with a view on the future (Hastings, 2014; Velde & Hooimeijer, 2010).

- **Large interventions**

  Large-scale adjustments to the current system, like replacements and renovations (Rijkswaterstaat, 2015c).

- **Multifunctional**

  Having many functions ("Multifunctional," 2017).

- **Multivariate simulation approach**

  A simulation approach having or involving a number of independent mathematical or statistical variables ("Multivariate," 2017).

- **Technical lifetime**

  The total time for which the asset is technically able to operate from its first commissioning (UNFCCC/CCNUC, 2009).

PART 1 - INTRODUCTION

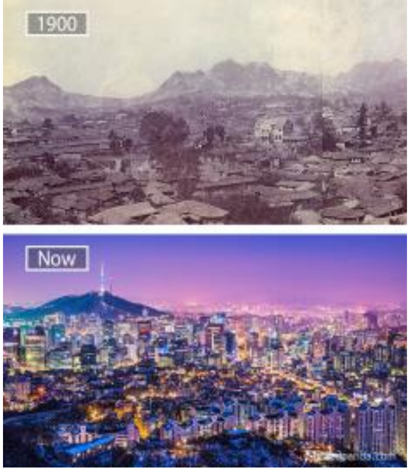
Dubai, United Arab Emirates

Shenzhen, China

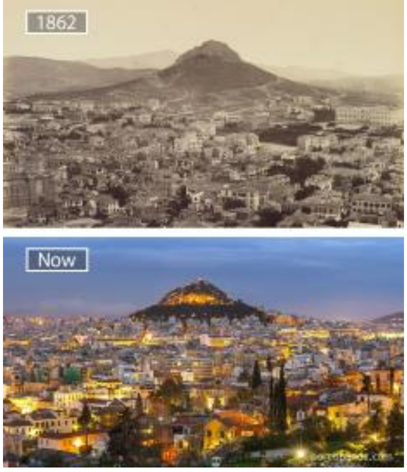
Fortaleza, Brazil

Abu Dhabi, United Arab Emirates

Seoul, South Korea



Athens, Greece



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1.1 PROBLEM STATEMENT

Cities are rapidly transforming, and infrastructures have to be adapted to these future developments. Some transform into megacities, inhabiting populations larger than 10 million. Countries as Brazil, India and China have experienced rapid urbanization flows in the last decades, and their existing infrastructures cannot accommodate these growths (Taubenböck et al., 2012; Wei, Huang, Li, & Xie, 2016; Zhao, Derudder, & Huang, 2017). Rapid population expansions in cities like Guangzhou (China) have increased the population size from 1.5049.000 inhabitants in 1950, to 12.926.800 inhabitants in 2013. Shenzhen (China) inhabited a population of 70.900 in 1979, this increased to 10.628.900 in 2013. These rapid urbanization flows were accompanied by a wide range of social and economic activities. The overconcentration of population and human activities has led to poor infrastructure, causing massive congestion problems (Kuroda, 1987; Taubenböck et al., 2012; Wei et al., 2016; World Population Review, 2017; Zhao et al., 2017).

The transformation of cities into megacities will continue on a global scale. In 2015 the world population consisted out of 7.38 billion people, in 2060 this amount is expected to grow towards 10.22 billion (UNDP, 2017). In 1975 there were 3 megacities, by 2011 this amount had grown to 27 megacities, located in each continent except Australia (Taubenböck et al., 2012).

The opposite behaviour can be witnessed during counter urbanization, which can cause a significant population decline within urban areas, creating possible financial problems, and leaving infrastructures without the required funds for upkeep. Counter urbanization can be caused by economic contraction, concurrent with the loss of industry and jobs (UNDP, 2016). Detroit used to be one of the major cities in the United States (1.8 million inhabitants in 1950), and jobs in abundance from automotive companies like Ford, General Motors, and Chrysler. Due to automation in factories, the 1970’s energy crisis, and the economic recession in the 1980’s, its welfare started to plummet. Today approximately 690.000 people live in Detroit (Padnani, 2013).

Natural disasters can also cause a rapid population decline. The city of New Orleans in the United States, experienced this after Hurricane Katrina hit in 2005. The city of Sendai experienced a similar decline after the 2011 earthquake and subsequent tsunami hit Japan (UNDP, 2016). However, in most cases a decline in population size is caused by low fertility rates. Between 2000 and 2016 over 55 cities with 500.000 inhabitants or more, showed a decline in population. This was predominantly witnessed in Europe, and was caused by low fertility rates (UNDP, 2016).

To adapt infrastructures to these kinds of future developments, infrastructure asset management can be applied. Infrastructure asset management aims at maximizing the performance of infrastructure asset systems in terms of functionality, for the energy, water and transport sector (Hastings, 2014). Furthermore, infrastructure asset management is concerned with applying technical and financial judgement to decide what infrastructure assets are needed to meet performance aims, and then to acquiring and logistically sustaining the assets over their whole life, through to disposal (Hastings, 2014).

Infrastructure asset managers require reliable insight in future developments, to perform strategic long-term planning of large intervention decisions. An example can be taken from Myanmar, which shifted its capital city from Rangoon to Naypyidaw, with its more strategic central position in the country. Large infrastructure systems were built far in advance, to accompany immense future urban migration streams. Highways with 20 lanes and grandiose boulevards were constructed. Yet, to date, the population has barely reached 1 million inhabitants, and more water buffalo than cars use the highways (Bruce, 2013; Kennard & Provost, 2015).

To plan large intervention decisions strategically in the long-term, multiple variables and their underlying relations need to be assessed, which creates dynamic complexity and uncertainty. The set of specific conditions for the area that infrastructure systems are situated in, can change dynamically over time due to different developments. These developments subject the strategic long-term planning of large intervention decisions to dynamic uncertainty (Bhamidipati, 2015; Bhamidipati, Lei, & Herder, 2016).

Developments in climate change can cause a decrease in technical lifetime for the infrastructure systems. Heavy precipitation can damage road surfaces, and thereby decrease its lifetime (Bles et al., 2015; Meyer et al., 2014). Extreme weather events can cause faster deterioration of the critical parts of lock systems (Glerum & Vrijburcht, 2000; Ooststroom, Annema, & Kolkman, 2008; Rijkswaterstaat, 2014c).

Developments in innovation can change the available capacities of infrastructure asset systems. They can improve the available capacity by more efficient use of existing area. Harbours can apply more innovative distribution systems, whilst using the same amount of area (Port of Amsterdam, 2015). Furthermore, innovative solutions can extend the technical lifetimes of existing infrastructures. Innovative asphalt layers can extend the technical lifetime of road systems (Rijkswaterstaat, 2016a). Locks can be equipped with modern synthetic materials and composites to extend their technical lifetimes (Rigo & Daniel, 2010).

Developments in population can increase, or decrease the amount of inhabitants in a city, requiring more, or less households, and thereby possibly limiting the available area. At the same time, more infrastructure will be required if population sizes increase, and limit the available area even more. Large intervention decisions will have to be implemented in time to ensure enough available area for the intervention. (Sambell, 2009; Stuurgroep Visie Noordzeekanaalgebied, 2013).

Developments in economy can create limitations for the available building space, and change traffic intensities. In growing economies harbours can require expansions to increase their distribution capacity. The harbour of Rotterdam required more distribution capacity, but had insufficient space in the city to expand. It therefore created the Maasvlakte in the North Sea with land reclamation techniques (CPB, NEI, & RIVM, 2001). Moreover, a growing economy can also change the traffic intensities for infrastructure systems. A growing economy can increase the amount of available jobs, and thereby increase the work related car trips or vice versa (Wester, 2016).

Developments in land use can cause system constraints for the expansion of infrastructure systems. Urbanisation requires more facilities, and thereby limits the expansion possibilities (Gemeente Amsterdam, 2011). The preservation of nature can become more, or less important, and limits expansion possibilities (Provincie Noord Holland, 2016).

Infrastructure systems from various different disciplines can influence each other due to their locational proximity, or dependency on other systems (Bhamidipati et al., 2016). This creates complexity for the long-term planning of large intervention decisions, which can change dynamically over time. The failure of one system in a network can cause a domino effect on other systems (Kennis voor Klimaat, 2014). This can be seen in the transport sector, which is becoming increasingly reliant on the electricity from the energy sector (URS, 2010). Furthermore, the disruption of roads, rails, or waterways can lead to the disruption of supplies or materials for other sectors (URS, 2010). Airports and harbours depend on the proper functioning of these infrastructure systems (URS, 2010). Another contributor to this dynamic complexity is the multifunctional nature of some infrastructure systems. These systems have to perform multiple functions, on multiple scales, simultaneously. Lock systems can be seen as a multifunctional infrastructure system. They can have a transport and flood protection function at the same time (Rijkswaterstaat, 2012b).

Asset managers base their long-term plans for large intervention decisions on decision support methods, which provide insufficient insight in the dynamic complexity and uncertainty, subjected to the infrastructure asset systems. Asset managers predominantly use decision support methods, which only consider single sector infrastructures and have a static nature that only considers an event or scenario of events with the highest probability of occurring at a certain place and time (Bhamidipati, 2015; Bhamidipati et al., 2016).

The ‘Reliability Centred Maintenance’ method (RCM), which includes the ‘Failure Mode, Effects ,and Criticality Analysis’ (FMECA) and the ‘Life Cycle Costing’ (LCC) tool, aims at finding the object(s) maintenance requirements and costs for the assets’ lifecycle in its operating context at a static point in time (Hastings, 2014; Moubray, 1997). The DISK and RINK tools are used to document the technical status of infrastructure systems at a static point in time, and thereby implement required interventions. Because these tools are based on static input information, they only focus on the scenario with the highest probability of occurring at that specific point in time (Rijkswaterstaat, 2015c; Tillema & de Lange, 2016). The Functional Lifetime Scenario Analysis (FLSA) method aims at finding the remaining functional lifetime of one, or maximum two functions, of single sector infrastructure asset systems. Moreover, it determines the functional lifetime on basis of the worst-case scenarios (Rijkswaterstaat, 2015c; Tillema & de Lange, 2016). Functional lifetime expectancies can be composed with the use of expert judgement. This method makes it very challenging to narrow down the required timing of interventions (Appendix E.2, interview Antea Group). A Cost Benefit Analysis (CBA) can be used to strengthen intervention decisions, but requires other tools for input. Moreover, it does not accurately reflect the available budget for an intervention (Appendix E.4, interview Rijkswaterstaat).

The PROBO technique, enables risk based operations and maintenance. With an FMECA critical parts of the system can be found, and interventions are ranked accordingly. However, this tool lacks the ability to make prognosis for decisions in the long-term (Appendix E.5, Interview Rijkswaterstaat (Bogaard & Akkeren, 2011). Trade Off Matrices (TOM) can be used to find the 'most optimal' intervention decision given some predefined criteria. This tool is static, and mostly only considers the worst case scenario (Appendix E.6, Interview BAM PPP).

A decision support method, able to incorporate all relevant dynamically changing complexity and uncertainties, is inadmissible for infrastructure asset management. Complexity and uncertainty will remain subject to infrastructure asset systems. This study defines uncertainty as the real world effects of assumptions over their plausible uncertainty ranges or sets (Pruyt, 2013). The uncertainty used throughout this study results from developments in climate, innovation, economy, population, and land use (Enriquez, Smit, & Ablett, 2015; Taubenböck et al., 2012; UNDP, 2017; United Nations, 2014b). This study defines complex systems as systems that are dynamic, tightly coupled, governed by feedback, nonlinear, history-dependent, self-organizing, adaptive, counterintuitive, policy resistant ,and characterized by trade-offs (Pruyt, 2013). The complexity used in this study results from the interconnection between the infrastructure asset systems, and their possible functions on multiple scales (Bhamidipati, 2015; Bhamidipati et al., 2016)

Not including all relevant complexity and uncertainties in the long-term planning can lead to wrongful interpretations, and thereby have severe consequences. Infrastructure asset systems are the backbone of national economies, provide connections for people and goods, access to jobs and services, and enable trading and economic growth (Fuggini et al., 2016). Furthermore, infrastructure asset systems have large design horizons, require a great amount of available space, and require large investments (Roovers & Buuren, 2014).

This study will assess the following objective, research question and hypothesis to address the necessity for a decision support method, able to incorporate all relevant complexity and uncertainty.

1.2 RESEARCH OBJECTIVE

The research objective for this study is formulated as:

"To analyse the contributions of a multivariate simulation method within the long-term planning of large intervention decisions in infrastructure asset management, by applying the combination of the ESDMA and adaptation pathways approach to the long-term planning for a network of complex multifunctional infrastructure asset systems subjected to dynamic uncertainty."

1.3 RESEARCH QUESTION

In line with the research objective, the research question for this study is:

"What can the combination of the ESDMA and adaptation pathways approach contribute to the long-term planning of large intervention decisions for complex infrastructure asset systems, subjected to dynamic uncertainty?"

1.4 HYPOTHESIS

To assess the research question, the following hypothesis was formed:

"*The long-term planning of large intervention decisions can be improved by assessing dynamic complexity and uncertainty with the combination of the ESDMA and the adaptation pathways approach."*

The adaptation pathways approach can improve the long-term planning of large intervention decisions, by adapting them to uncertainty, for complex issues and systems. With the adaptation pathways approach, decision makers can identify opportunities, no regret actions, lock-ins, and the timing of an action, in order to support decision-making for complex issues in uncertain changing environments (Haasnoot, Kwakkel, Walker, & Maat, 2013)

ESDMA can assess the dynamic complexity and uncertainty subjected to infrastructure asset systems, and thereby support the adaptation pathways approach. ESDMA combines System Dynamics (SD) with Exploratory Modelling and Analysis (EMA), which enables the use and development of SD models, for analysing dynamic complexity and deep uncertainty (Kwakkel & Pruyt, 2013)

In this study the hypothesis will be assessed by identifying the main challenges in the long-term planning of large intervention decisions within infrastructure asset management (section 2.1), applying the ESDMA and adaptation pathways approach to a case study (section 2.2 & 2.3 and part 3), and reflecting the results of the followed approach to the main challenges (part 4).

1.5 THESIS OUTLINE

This thesis is structured around four main parts, including this introduction part, and is build up in such a way that proper assessment of the hypothesis is possible.

Part 2 builds on the methodology used for this research and the case study. First, the current practices of infrastructure asset management are elaborated, which frame the main challenges within the field of long-term planning of large intervention decisions in infrastructure asset management. Second, the used approach will be explained. The applied approach consists of a combination of the ESDMA and adaptation pathways approach. The combined approach forms the common thread of the following chapters in this thesis. Last, the case study is described to which the combined approach will be applied. The case study includes a highly schematised representation of the city of Amsterdam, including its connecting infrastructure systems. The case study is exposed to a set of future uncertainties, which can be summarised in a set of scenario packages. The scenario packages will be used when forming the adaptation pathways maps.

Part 3 elaborates the computational model used to analyse the impacts of future uncertain developments subjected to the case study. The computational model consist out of six sub-models, the city, harbour, area, economy, road and lock sub-model. The chapter starts with a general model description, including a sector diagram representing the six sub-models, and their interconnections. This is followed, by a description of the key performance indicators by which intervention policies are tested. Then, the structures, feedbacks and dynamics of the six sub-models are presented. Finally, the verification and validation of the model and the consequent experimental setup of the model is explained.

Part 4 provides the results of this study. The results are formed by performing EMA simulations on the computational model. The results part reflects the followed combined approach to the main challenges identified in the current asset management practices. Part 4 is split up into multiple sections. Section 4.2 & 4.3 provide insight in the possible assessment of dynamic complexity and uncertainty subjected to the infrastructure systems. Section 4.4 provides insight in the possible improvement of large intervention decisions, by adapting them to dynamic uncertainty and complexity, with help of the adaptation pathways approach.

Finally, based on the main conclusions, a number of recommendations for this field of work are given. The main focus is on the contributions that the combined approach has within the field of infrastructure asset management.

PART 2 – METHODOLOGY & CASE STUDY

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2.1 CURRENT PRACTICES INFRASTRUCTURE ASSET MANAGEMENT

This study applies the ESDMA and adaptation pathways approach as decision-support method within the field of infrastructure asset management. The applied approaches and the field of infrastructure asset management are extensive, and have a long history. However, applications of these specific approaches within the field of infrastructure asset management are limited. In this section the field of infrastructure asset management will be generally described, current practices of decision-making in infrastructure asset management will be listed, and the challenges associated with making large intervention decisions within infrastructure asset management are presented. These insights are presented in this part of the report, since they are linked to the actual used methodology (section 2.2). The challenges associated with making large intervention decisions within infrastructure asset management were obtained from literature and expert interviews.

Infrastructure asset management is a coordinated activity of an organisation, which aims at realising the maximum performance of infrastructure asset systems, during their whole lifecycle, by the balancing of costs and risks (IAM, 2015). Organisations implement hierarchical asset management systems to realise the maximum performance of infrastructure asset systems. The hierarchical asset management system aims at making intervention decisions at network level for a portfolio of assets, while performing lifecycle activities at operational level to manage assets over their lifecycles (IAM, 2015; Appendix E.5, Interview Rijkswaterstaat). The performance of the asset has to be maximised, in order to reach maximum value of the asset, by ensuring the maximum level of service (Hastings, 2014; ISO, 2014). Asset performance can be measured in terms of level of service; a low service level thereby entails a low performance of the asset. This can be seen in road systems with high congestion probabilities, which lead to high cost effects and thereby have a low performance (Rijkswaterstaat, 2015a). Moreover, lock systems with insufficient capacity can induce long waiting times for vessels, and thereby lead to high cost effects. In both cases, the performance is not maximised, and maximum value is not realized (Rijkswaterstaat, 2011). The asset is managed throughout the whole lifecycle, from acquisition, through disposal, in order to balance costs and risk, by ensuring asset performance under changing conditions (Hastings, 2014). Asset performance has to be updated during its lifecycle. Costs, and risks involved with interventions have to be timely adapted (Buuren & Roovers, 2015; Hastings, 2014).

To realise maximum performance of infrastructure asset systems, organisations make a long-term planning for intervention decisions on the basis of information attained by decisions support tools. Organisations are required to use appropriate combinations of decision-support tools (IAM, 2015) to obtain information about the assets current situation, and developments in terms of the technical and service expectations of the asset system (Hastings, 2014). The information obtained by decision support tools is then used to balance performance based intervention decisions, by their costs and risks. Decision support tools provide information about the functional, or technical intervention threshold, for either the main, or secondary function(s) of the asset (Hastings, 2014). The functional performance of the main transportation function of infrastructure assets can be measured with the intensity/capacity factor. If this factor grows above a certain threshold an intervention is required. Furthermore, interventions can be implemented if the end of technical life for the infrastructure asset system is reached. If an infrastructure system is multifunctional, the secondary function can require interventions as well. If a lock has sufficient capacity for its transportation function, but insufficient retaining height for its flood protection function, an intervention is required. Road systems can require extra interventions if the underlying sewer system has insufficient discharge capacity for rainwater.

In order to balance the performance oriented intervention decisions, timing of the intervention is essential. Costs associated with interventions hold lower net present values when implemented as late as possible. This is due to the time value of money. However, interventions have to be performed in time to assure the functionality of a system. Moreover, if an intervention for one function of a system is performed, it might be more economically viable to extend the functional and technical lifetime of secondary functions at the same time (Bhamidipati, 2015; Bhamidipati et al., 2016; Brealey, Myers, & Allen, 2011; Kennis voor Klimaat, 2014).

As presented in the introduction, the decision support tools commonly used to maximize the performance of infrastructure asset systems are of a static nature, and only consider single sector infrastructures. These tools provide insufficient insight in the dynamic complexity and uncertainty subjected to an asset system, in order to realise the required maximum performance of the asset system. Complexity mainly results from the complex nature of infrastructure asset systems, the influence of interfaces between other infrastructure asset systems, and their functions on multiple scales. Uncertainty mainly results from the future developments that are subjected to the environment that infrastructure asset systems are situated in.

When interviewing policy makers within the field of infrastructure asset management, the necessity for a decision support tool able to incorporate dynamic complexity and uncertainty could be obtained. The primary finding concerning uncertainty was that policy makers perceive the choice between different intervention policies as challenging. This is mainly caused by the uncertain magnitude and time of occurrence of relevant developments. Therefore, in current practices, large bandwidths on developments are used to minimize risks (Appendix E.2, Interview Antea Group; Appendix E.5, Interview Rijkswaterstaat). The decisions concerning unpredictable future developments, are predominantly made by overdesigning for the worst case scenario. However, overdesigning can be very costly and unnecessary (Appendix E.1, Interview Province of North Holland). The main challenge for decision support tools lies in finding insight in the many variables and uncertainties. It can be very challenging to make the right decision with so many input (Appendix E.5, Interview Rijkswaterstaat). The secondary finding concerning complexity was that policy makers recommend that intervention decisions are made on a network level, but perceive it as very challenging to translate these plans to an operational level. Decisions on a high aggregation level can minimize unnecessary interventions in the same area, and can incorporate the effects on different asset systems. However, this can be challenging since infrastructure systems have multiple interfaces, and can have multiple functions. It is therefore important that decision support tools stimulate stakeholders of different asset systems to develop a shared policy on a system level instead of object level (Appendix E.2, Interview Antea Group; Appendix E.5, Interview Rijkswaterstaat).

When considering real world events, the necessity for a decision support tool able to incorporate dynamic complexity and uncertainty can be obtained as well. An example can be taken from the city of Houston in the United States. Houston has experienced rapid growths in the last years, and has built many houses and roads as response. The majority of these paved constructions was built in the suburbs, where floodplains enabled safe outflows of the water infrastructure during extreme weather events. As a result the city experienced massive floods, with disastrous consequences after it was hit by Hurricane Harvey in august 2017. Even though hurricanes can be considered as extreme weather events, it is possible to adapt to these kind of phenomena. Furthermore, climate change can induce more of these extreme weather events globally. Complex infrastructure systems from the water, transport and energy sector have to be able to adapt to dynamically changing future uncertainties (Boburg & Reinhard, 2017; Patterson, 2017).

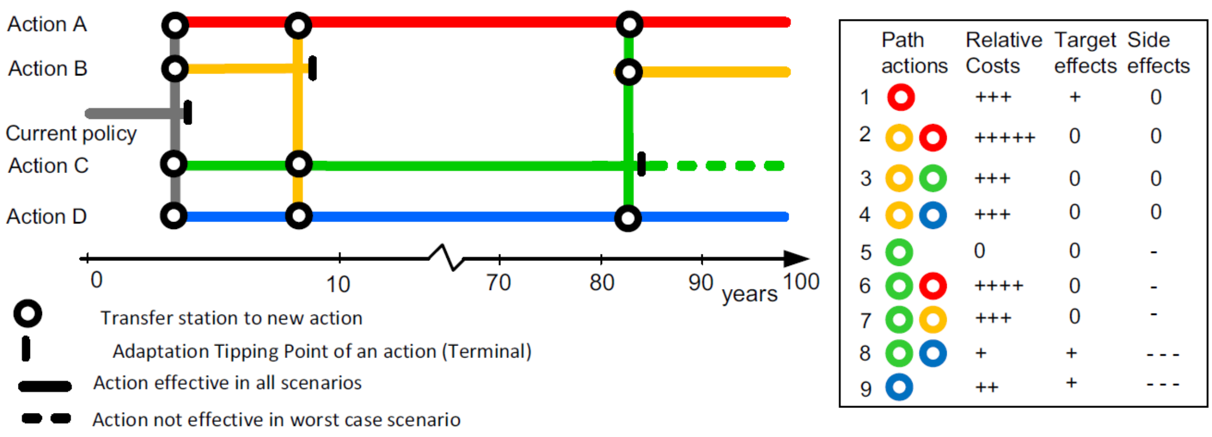
The following section presents the proposed method for incorporating dynamic complexity and uncertainty during the long-term planning of large intervention decisions within the field of infrastructure asset management.

2.2 METHODOLOGY

There are various possible approaches that can assess the dynamic complexity, and uncertainty within the long-term planning of infrastructure asset systems. This research uses the adaptation pathways approach and the ESDMA approach. The methodology behind these approaches will be explained in this chapter, together with the reasoning of choice. The steps that were used in this research, are shown in an overview in §2.2.3. All steps are performed on a case study, which is further explained in section 2.3.

2.2.1 THE ADAPTATION PATHWAYS APPROACH

This research applies the adaptation pathways approach as an overall decision support method for adapting the long-term planning of large intervention decisions within infrastructure asset management, to dynamic complexity and uncertainty. The adaptation pathways approach is an analytical framework that helps position short- and medium-term policy decisions within longer term strategic ambitions (Haasnoot et al., 2013; Hermans, Haasnoot, ter Maat, & Kwakkel, 2017). The adaptation pathways approach considers multiple long term pathways, which each have the potential to fulfil long-term ambitions under changing conditions (Hermans et al., 2017). Long-term pathways start with the currently applied policy, which after a certain time can be expected to no longer meet its specified objectives. At this time a so-called tipping point is reached. When a tipping point is reached, a switch has to be made to a new policy, which thereby adapts the pathway to changing conditions (Haasnoot et al., 2013; Hermans et al., 2017). The adaptation pathways approach prepares a plan for actions to be taken immediately, and for preparations that enable the implementation of an action in the future, in case conditions change (Haasnoot et al., 2013). The choice between the long-term pathways can be made on relative lifecycle costs, target effects ,and side effects (see Figure 2).



	Path actions	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟡 🔴	+++++	0	0
3	🟡 🟢	+++	0	0
4	🟡 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟡	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map

Scorecard for pathways

Figure 2. Example of adaptation pathways map (Haasnoot et al., 2013)
On the left, policy actions are listed. Each policy combination is scored in the scorecard. The scorecard presents the relative lifecycle costs, target effects ,and side effects for the path actions.

When comparing the adaptation pathways approach to other approaches, it deals with a highly dynamic nature and high level of uncertainty, and can support the Dynamic Adaptive Policy Pathways (DAPP) approach for incorporating deep uncertainty (Walker, Haasnoot, & Kwakkel, 2013). A recent study reviewed a wide variety of planning approaches on the basis of their dynamic nature and level of uncertainty (Walker, Haasnoot, et al., 2013). This particular study concluded that the adaptation pathways approach can incorporate highly dynamic behaviour in deeply uncertain conditions (Haasnoot et al., 2013; Kwakkel & Haasnoot, 2012; Kwakkel, Haasnoot, & Walker, 2016). Dynamic meaning that the adaptation can be anticipatory concurrent and reactive (Walker, Haasnoot, et al., 2013). The level of uncertainty specifies the degree of uncertainty. It can range from low, well characterized uncertainty, to deep uncertainty, and even recognized ignorance (Walker, Haasnoot, et al., 2013). The approach that is able to deal with the highest dynamic nature and uncertainty level was the DAPP approach. This approach is an extent for the use of the adaptation pathways. This approach extends the pathway by determining contingency actions and triggers, specifying a dynamic adaptive plan, implementing the plan, and monitoring the plan. This approach can only be used for real world ongoing projects, and is therefore not used in this thesis. In real world projects it is recommended to extend the use of the adaptation pathways method with the DAPP approach (Haasnoot et al., 2013; Walker, Haasnoot, et al., 2013).

Other approaches as the Assumption Based Planning (ABP) have a more static nature in which the adaptation is primarily anticipatory. The approach covers static robustness, since it analyses the critical assumptions of an existing plan, but does not continue to be used to cope with changes in the world (Walker, Haasnoot, et al., 2013). This static/robust nature was found for the Robust Decision Making (RDM) approach as well. This approach does not explicitly consider the dynamic adaptation of a planning over time. It aims at developing a static plan rather than a dynamic plan (Walker, Haasnoot, et al., 2013). Various other approaches were analysed, which all showed a low score on their dynamic nature, and/or their uncertainty level. Furthermore, no other approach could be extended by the DAPP approach.

The adaptation pathways approach has supported decision-making for complex issues under dynamic uncertain global and regional changes (Haasnoot et al., 2013). The approach was used for various cases, including the Dutch Delta program for water security and safety in the Netherlands (Haasnoot et al., 2013). It was applied for adapting a development planning to future uncertainties in Indonesia (Butler et al., 2016). Furthermore, this approach was used for adapting urban water supply systems to climate change in London (Kingsborough, Borgomeo, & Hall, 2016).

2.2.2 EXPLORATORY SYSTEM DYNAMICS MODELLING AND ANALYSIS (ESDMA)

Exploratory System Dynamics Modelling and Analysis (ESDMA) is used for supporting the adaptation pathways approach, by addressing the dynamic uncertainty and complexity, subjected to infrastructure asset systems. The ESDMA approach combines Exploratory Modelling and Analysis (EMA) and System Dynamics (SD) (Sterman, 2000).

This combined approach can be used to support the development of adaptation pathways by addressing dynamic uncertainty and complexity (Kwakkel & Haasnoot, 2012; Kwakkel & Pruyt, 2013). SD models are very useful for simulating dynamically complex issues, EMA allows to extend the use of SD models for deeply uncertain issues (Pruyt & Kwakkel, 2012)

ESDMA has supported decision-making, by addressing dynamic uncertainty and complexity, in various cases, and issues. ESDMA has, amongst other cases, been used for discovering different types of dynamics related to metal and mineral scarcity (Kwakkel & Pruyt, 2013). It has been used for worst-case discovery in water scarcity (Kwakkel & Pruyt, 2013). ESDMA has been used to foster understanding of possible dynamic behaviours of 'concerted' bank runs and to perform rough-cut policy/strategy analyses (Pruyt & Hamarat, 2010). Moreover, ESDMA has been used to assess the implications of the US' shale gas revolution on intrastate stability within traditional oil- and natural gas-exporting countries in the EU neighbourhood (Jong et al., 2014).

Within ESDMA, Exploratory Modelling and Analysis (EMA) is applied, for addressing the dynamic uncertainty subjected to infrastructure asset systems, and thereby supporting the adaptation pathways approach. EMA can extend the use of computational models, by generating tens of thousands of scenarios in view of exploring and analysing this ensemble of all plausible futures, and testing the robustness of decisions in the entire uncertainty space. (Bankes, 1993; Kwakkel & Pruyt, 2013; Lempert, Popper, & Bankes, 2003; Pruyt & Kwakkel, 2012). In order to perform tens of thousands of simulations with the EMA workbench, computational models and programming language are required (Pruyt & Kwakkel, 2012)

The EMA workbench will be used in combination with Python programming language, to apply EMA based computer simulation. The computational model will be built with SD, as is explained in the next paragraph. Python is an open-source high-level programming language through which computational models can be controlled (Kwakkel & Pruyt, 2013). The EMA workbench is preferred, because of its convenience in easily specifying the uncertainties and their ranges, including categorical or integer-based ranges, its ease of storing results, its open source ,and the support it offers for subsequent analysis of the results using various machine learning algorithms and visualization techniques (Kwakkel & Pruyt, 2013). EMA has supported decision-making, by addressing dynamic uncertainty in various cases and issues. Some of these cases include the identification of policy options against climate change, that are acceptable to a wide variety of countries, and robust across a wide variety of different future climate change developments (Lempert et al., 2003). The assessment of reduction policies for CO_2 in the Dutch household sector (Agusdinata, 2008), and the Dutch electricity systems (Kwakkel & Yücel, 2014). EMA has been used for creating insight in the uncertainty of the European biodiesel market (Vita, Kwakkel, & Van Beers, 2015).

Within ESDMA, a System Dynamics (SD) model will be applied, for extending the use of the EMA workbench, by addressing the dynamic complexity of infrastructure asset systems, and thereby supporting the adaptation pathways approach. SD is a multivariate computer simulation method, which can be used to describe, model, simulate, and analyse the structure of dynamically complex issues and/or systems, accompanied by the time evolutionary behaviour resulting from the systems own structure (Kwakkel & Pruyt, 2013; Pruyt, 2013). The structure and time evolutionary behaviour of a system is computationally simulated in SD, by using causal loops, and state variables, which represent complex feedback mechanisms as can be seen in real complex issues. (Jong et al., 2014; Kwakkel & Pruyt, 2013). Complex issues, with feedbacks and many variables are fallible for mental simulation, and thereby require computational simulation (Kwakkel & Pruyt, 2013). A repository with the SD model developed in this study, can be found on https://github.com/Mhavelaar/ThesisIAM.

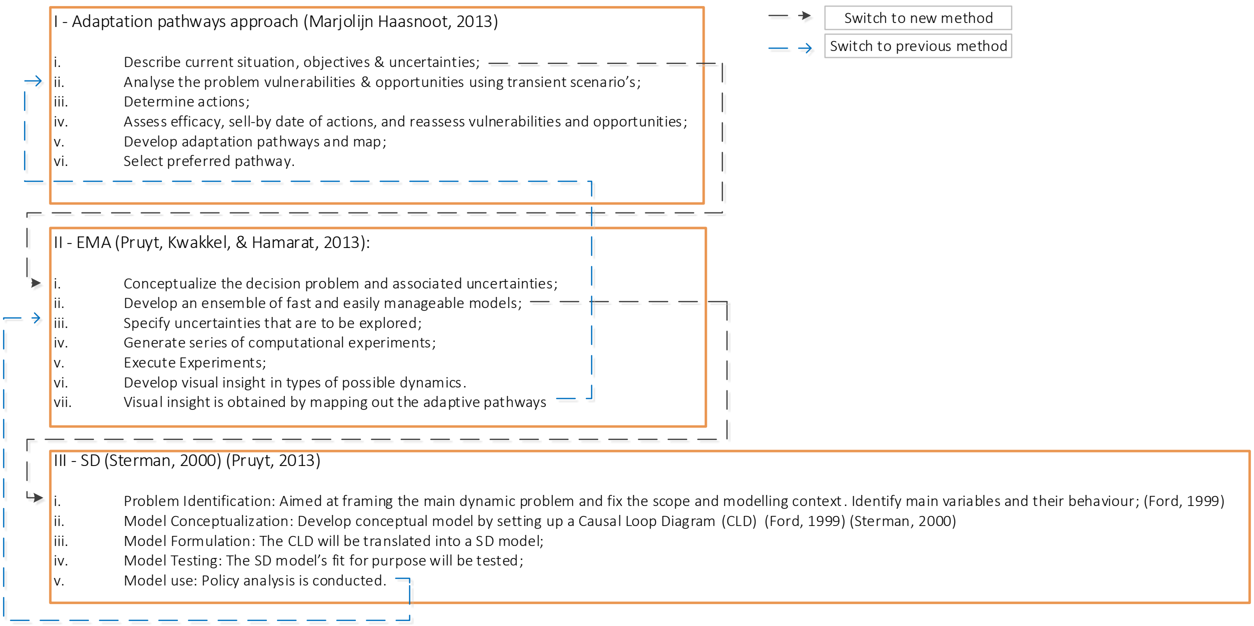
Vensim will be used as SD computer based simulation, and thereby extend the use of the EMA workbench, by providing computational models that address dynamic complexity. The EMA workbench requires computational models that can assess the complexity of systems, and can be used in combination with Vensim and Excel. VENSIM (SD) will be used in combination with the EMA workbench. VENSIM is an open-source tool able to support the entire modelling process, by incorporating complexity (Eberlein & Peterson, 1992). The advantage of the tool in relation to other tools is that it generates quick understanding of the model because of its simple usability (Eberlein & Peterson, 1992). This enables a wider use within infrastructure asset management. Excel will not be used in combination with the EMA workbench since it is not open source, and cannot create a model structure with endogenous scenario implementations. Netlogo and Repast will not be used in combination with the EMA workbench. The use of Netlogo and Repast in combination with the EMA workbench is still being planned (Kwakkel, 2011).

SD allows to identify desirable system changes in complex systems and/or issues from various important application domains, test them virtually, and thus supports decision making (Pruyt, 2013).

SD has application domains in health policy, energy transitions, and resources scarcity, environmental and ecological management, safety and security, public order and public policy, social and organizational dynamics, education and innovation, economics and finance, organizational and strategic business management, information science, and operations and supply chain management (Pruyt, 2013). In the health domain it has been used for the diffusion of the epidemic disease (MERS-CoV) outbreak in South Korea (Shin, Kwag, Park, & Kim, 2017). In the environmental management domain it has been used to create insight in the CO_2 emission trends in China's primary aluminium industry. Furthermore, it has been applied for urban water system management in Bosnia and Herzegovina (Rozic, Margeta, & Knezic, 2015). Various other cases in the different domains exist in literature.

2.2.3 COMBINED APPROACH

The combined approach used within this study follows multiple steps for both the adaptation pathways approach and the ESDMA approach. All steps are performed for a fictional case study, which is further elaborated in section 2.3. Part of the steps overlap, and some steps have to be performed iteratively. The steps used in the ESDMA approach can be divided into EMA and SD. Underlying overview (Figure 3) presents the steps taken per used method, and the order in which the steps were taken throughout this study.



I - Adaptation pathways approach (Marjolijn Haasnoot, 2013)

i. Describe current situation, objectives & uncertainties;
ii. Analyse the problem vulnerabilities & opportunities using transient scenario's;
iii. Determine actions;
iv. Assess efficacy, sell-by date of actions, and reassess vulnerabilities and opportunities;
v. Develop adaptation pathways and map;
vi. Select preferred pathway.

II - EMA (Pruyt, Kwakkel, & Hamarat, 2013):

i. Conceptualize the decision problem and associated uncertainties;
ii. Develop an ensemble of fast and easily manageable models;
iii. Specify uncertainties that are to be explored;
iv. Generate series of computational experiments;
v. Execute Experiments;
vi. Develop visual insight in types of possible dynamics.
vii. Visual insight is obtained by mapping out the adaptive pathways

III - SD (Sterman, 2000) (Pruyt, 2013)

i. Problem Identification: Aimed at framing the main dynamic problem and fix the scope and modelling context. Identify main variables and their behaviour; (Ford, 1999)
ii. Model Conceptualization: Develop conceptual model by setting up a Causal Loop Diagram (CLD) (Ford, 1999) (Sterman, 2000)
iii. Model Formulation: The CLD will be translated into a SD model;
iv. Model Testing: The SD model's fit for purpose will be tested;
v. Model use: Policy analysis is conducted.

Figure 3. Graphic overview of the combined approach presenting the steps followed in this study (Ford, 1999; Haasnoot et al., 2013; Pruyt, 2013; Pruyt, Kwakkel, & Hamarat, 2013; Sterman, 2000)

The combined approach will be applied to a case study, to assess the hypothesis as was described in section 1.4.

2.3 CASE STUDY

To enable the assessment of dynamic complexity and uncertainty with the proposed combined approach, a case study will be used. This chapter will describe the case study that was used during this study. First, an introduction will be provided to the case study. Second, future uncertainties and systems constraints that will be subjected to the case study will be presented. Third, the future uncertainties will be combined into scenario packages, which will be used during the formation of the adaptation pathways.

2.3.1 INTRODUCTION TO CASE STUDY

The hypothetical case study used during this thesis is a highly schematized representation of the city of Amsterdam, with its connecting infrastructure asset systems. The city incorporates a population, houses, green space and businesses. Various interconnected infrastructure systems as a harbour, lock, road, canal ,and rail system are situated in, and around the city. The asset systems are all connected to the harbour system, and thereby influence each other. A graphic overview of the case study is presented in Figure 4.

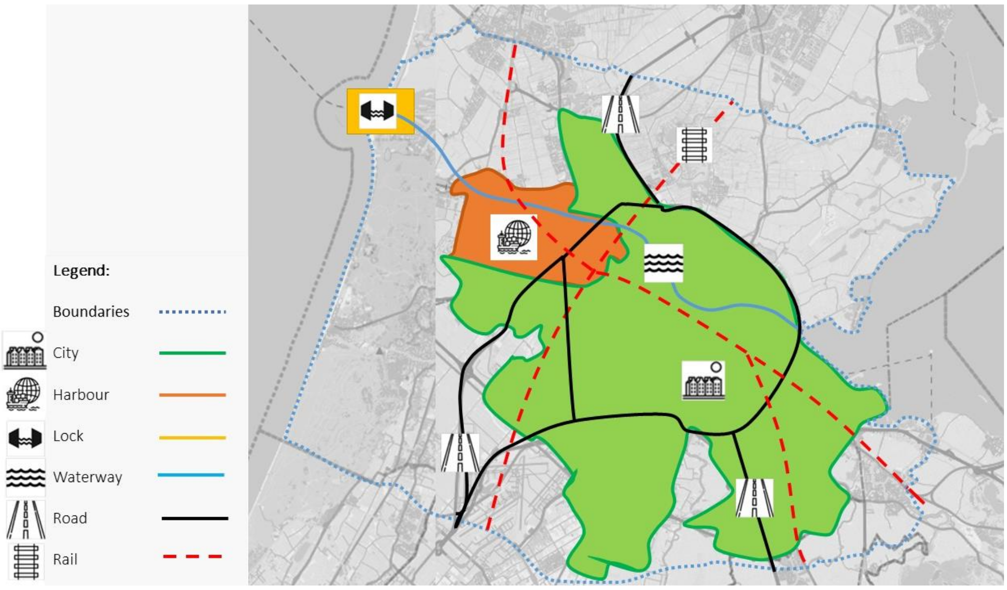


Figure 4. Graphic overview of the case study, representing the city with its infrastructure assets
The city (green) is a schematised representation of the city of Amsterdam. The infrastructure assets that are connected to the city, are the harbour (port of Amsterdam, orange), the lock (lock IJmuiden, yellow), the waterway (Noordzeekanaal, blue), the road (A10, including parts of the A8, A6, A4, and A5, black) and the rail (red). The dotted blue line presents the total area for which the case study is conducted.

The city is roughly based on the city of Amsterdam. The city is situated in area prone to flood risk, and is therefore protected by flood control structures. Large naval and road traffic intensities are present in the city, ensuring trade and business activities (OIS Amsterdam, 2016).

The harbour schematically represents the port of Amsterdam. Currently, the harbour is the 4th largest harbour in Europe, and wants to constantly expand. It is connected to the infrastructure asset systems, and is an important contributor to the local economy (Port of Amsterdam, 2015).

The canal schematically represents the Noordzeekanaal. In this case study it is assumed to be wide and deep enough for all growth in vessel size. Furthermore, the capacity of the canal is sufficient to support all future growth of naval traffic intensities.

The lock schematically represents the lock complex of IJmuiden with its four separate locks (Kleine sluis, Zuidersluis, Middensluis and Noordersluis). The first function of the lock is to support safe naval traffic to, and from the harbour. In order to do so, the locks need to be able to accommodate the ongoing growth of vessel size, and generate enough capacity. Currently, the biggest sea lock in the world is being constructed at IJmuiden, and is expected to finish in 2019. More interventions might be required in the future, if the harbours demand keeps increasing. Moreover, more interventions can be required when existing locks reach their end of technical life. The Noordersluis was severely damaged during WOII, and will reach its end of technical life around 2030. The other locks were recently renovated, and are expected to reach their end of technical life in a later stadium. In addition to its transport function, the lock has a flood protection function. The lock complex is an important flood control structure in the Netherlands, and will have to retain future flooding events (including sea level rise) (Rijkswaterstaat, 2008, 2012b; Appendix E.6, Interview BAM PPP).

The road schematically represents the road network around the city of Amsterdam. The road network consists mainly of the ring road A10, including parts of the connecting roads from, and to the hinterland, and the harbour (A8, A5, A4, A2) (Rijkswaterstaat, 2017c). The main function of the road network is to enable fast, and safe transport of cars, and trucks. In this case, the main performance requirement for the road network is to ensure sufficient capacity, in terms of functionality, and technicality. Currently, road interventions are performed at the ring road A10, to extend the technical lifetime (Rijkswaterstaat, 2017a).

The asphalt layer is being replaced, traffic systems are checked and replaced, and the sewer system is enlarged to ensure sufficient rainwater flow capacity. The sewer system is part of the secondary function of the road, which includes discharging rainwater from the road surface, to prevent flooding.

The rail schematically represents the rail system of Amsterdam. In this case study it is assumed that the rail system has sufficient capacity for future growth in cargo traffic. The transportation function of people is not taken into account during this study (Rijkswaterstaat, 2012b).

The infrastructure asset systems will have to be adapted to the uncertain and complex future developments of the city and other exogenous factors. The uncertainties will result from developments in economy, climate change, innovation, land use, and population. These developments can influence the pressure on the capacities of the infrastructure asset systems. The complexity will result from the influence of interconnected systems due to their local proximity, or dependencies. Furthermore, the infrastructure systems can have multiple functions on different scales.

To ensure the technical and functional performance of the infrastructure systems, a long-term planning of interventions will have to be made. The implementation time of these interventions is of high importance. Limited space is available for the development of the city and its infrastructure. Changes in population, economic growth, land use, innovation, and climate can affect the pressure on the available area. Furthermore, these developments can change the traffic intensities for the infrastructure asset systems, and thereby affect its functionality. Higher traffic intensities can cause the I/C factor of the infrastructure systems to rise above its threshold, and thereby induce new required interventions. The technical lifetime of infrastructure systems can change dynamically over time, and can thereby influence the capacity of the system. The technical lifetime of infrastructure systems can be influenced by the intensity of its use, climate change, and various other factors. Renovations and replacement interventions have to be performed in time to assure the technical lifetime of the infrastructure systems. Moreover, the quality or state of a system can affect the amount of capacity available.

The emphasis in this case study will lie on the lock and the road system. In particular, on forming a long-term planning for large intervention decisions on these systems, to ensure their (technical) functionality under changing future developments. The canal and rail system are used as distribution mechanisms for the harbour, but will not be subjected to interventions. In other words, it is assumed they have sufficient capacity for future developments, and never reach their end of technical lifetime. The harbour and city will be used as performance indicators to measure the performance of the infrastructure systems. The development of the harbour and the city is therefore, as in many cities, dependent on the well-functioning of the infrastructure systems. Moreover, the harbour and the city influence the infrastructure, and vice versa. All aspects, relations, and feedbacks of the case study will be explained more extensively in part 3 (Model Building).

2.3.2 FUTURE UNCERTAINTIES & SYSTEM CONSTRAINTS

This section describes the future uncertain developments and constraints that will be projected onto the case study. Together with the system characteristics and objectives in the current situation, the associated decision problems will be determined. The uncertain developments and constraints will represent the dynamically changing environment that the infrastructure systems are situated in. Future uncertainties resulting from climate, innovation, population, economic ,and land-use developments, may impose an effect on the (technical) functionality of the asset systems, and thereby cause system constraints. Future uncertain developments can change the specific characteristics of the environment an asset system is situated in. This can affect the functioning of asset systems and interconnected asset systems (Bhamidipati, 2015; Bhamidipati et al., 2016; Kennis voor Klimaat, 2014). The future uncertain developments are taken into consideration until the year of 2060, the reasoning behind this choice is presented in section 3.9.

Future climate developments can vary in magnitude, and affect the functional and technical lifetime of infrastructure asset systems, whilst imposing system constraints. Climate developments can affect the functional and technical lifetime of infrastructure asset systems by influencing their capacities. Climate developments that impose the largest effects on the infrastructure assets in this case study are: precipitation (intensity) increases and sea level rise (Kennis voor Klimaat, 2014). Climate developments can affect the functional lifetime of infrastructure assets by influencing the level of service, which is determined by the performance of the asset in its functional environment. Furthermore, climate developments can affect the technical lifetime of infrastructure assets by causing early deterioration of the asset (Bles et al., 2015; Kennis voor Klimaat, 2014; Meyer et al., 2014).

Climate change can impose a system constraint for infrastructure assets because of the changes in amount of land used for retention areas. Sea level rise and higher precipitation intensities increase water levels, which require the reservation of areas for water retention.

In table 1, climate developments are divided into a low, medium, and high scenario. In a low climate scenario (G_L), small temperature increases, and small changes of the air circulation are expected, which thereby cause small increases of precipitation, and small increases of sea level (IPCC, 2014; KNMI, 2015). In a medium climate scenario (G_H), small temperature increases, and large changes of the air circulation are expected, which thereby cause moderate increases in precipitation, and small increases of sea level (IPCC, 2014; KNMI, 2015). In a high climate scenario (W_L, W_H), large temperature increases, and changes of the air circulation are expected, which thereby cause large increases of precipitation, and large increases of sea level (IPCC, 2014; KNMI, 2015).

Future innovation developments can vary in magnitude, and affect the functional and technical lifetime of infrastructure asset systems, whilst imposing system constraints. Innovation developments can affect the functional lifetime of infrastructure asset systems by influencing the assets capacities. The application of innovative solutions can increase the capacity of an asset system in its available space. Automated driving can increase the capacity of road systems. Innovations related to faster lock cycles can increase the capacity of lock systems. Efficient distribution systems can increase a harbours capacity (Milakis, Arem, & Wee, 2017; Port of Amsterdam, 2015; Rigo & Daniel, 2010; Rijkswaterstaat, 2016a). Innovation developments can affect the technical lifetime of infrastructure asset systems by extending it. Innovative asphalt layers can extend the technical lifetime of existing roads. The use of modern synthetic materials and composites can decrease contact wear, and corrosion for lock systems. (Rigo & Daniel, 2010; Rijkswaterstaat, 2016a) Innovation developments can impose a system constraint for infrastructure assets because of the amount of land used by the asset systems. Innovative solutions can enable assets to deal effectively with their used land, this entails less land use by infrastructure asset systems. Limited innovation can thereby cause a system constraint, by requiring more land for the same performance level (Rijkswaterstaat, 2016a). In table 1, innovation developments are divided into a low, medium, and high scenario.

Future population developments can vary in magnitude, and affect the functional and technical lifetime of infrastructure asset systems, whilst imposing system constraints. Population developments can affect the functional, and technical lifetime of infrastructure asset systems, by influencing their traffic intensities. Changes in traffic intensity of leisure vessels and cars, will directly influence the functional, and indirectly the technical lifetime of transport systems as the lock and the road. Population developments can impose a system constraint for infrastructure assets because of the changes in amount of land used by cities. Cities will have to cope with population developments, and thereby need to adjust the amount of spacing used for houses/housing density. Populations also affect the economy, which could have a positive effect on business growth. In both situations, land will have to be used for the development of the city, which can constrain the expansion possibilities of the infrastructure systems.

In table 1, population developments are divided into a low, medium, and high scenario. In a low population scenario, immigration rates remain limited. The population will face the effects of obsolescence, which causes the death rate to increase. Small birth rates and high death rates will likely cause the population size to decline (Stoeldraijer, Duin, & Huisman, 2016). In a medium population scenario, immigration rates remain moderate. The population will still face the effects of obsolescence, which causes the death rate to be larger than the birth rate. The population size will probably remain the same in this scenario (Stoeldraijer et al., 2016). In a high population scenario large immigration rates are expected, which thereby impose an increased birth rate relative to the total population. Moreover, it is expected that the average life expectancy of people will grow due to progress in healthcare (a lower death rate). In this scenario it is likely that the population size will increase (Stoeldraijer et al., 2016).

Future economic developments can vary in magnitude, and affect the functional and technical lifetime of infrastructure asset systems, whilst imposing system constraints. Economic developments can affect the functional, and technical lifetime of infrastructure asset systems, by influencing their traffic intensities. Economic growth can influence the amount of distribution demand for the harbour. The amount of demand can influence the traffic flows towards, and from the harbour. Flow demands for the connecting asset systems (e.g. lock and road) will thereby change. Economic growth can indirectly influence the technical lifetime of asset systems. Higher traffic intensities lead to faster deterioration of the infrastructure.

Economic developments can impose a system constraint for the infrastructure systems, because of the change in amounts of land used by the city and harbour. Economic growth can be a driver for city expansion (more businesses, housing and harbour area). Infrastructure assets will have to accommodate this city growth in less available area.

In table 1, economic developments are divided into a low, medium, and high scenario. In a low scenario, limited yearly macro-economic growth is expected. This limited growth will mainly be caused by limited technological developments, and a limited population growth (CPB/PBL, 2015). In a hard scenario, large yearly macro-economic growth is expected. This high economic growth will mainly be caused by large technological developments, and a growth in labour population (CPB/PBL, 2015). In a medium scenario, moderate yearly macro-economic growth is expected. This moderate economic growth will be caused by moderate technological developments, and a stabilisation in labour population (CPB/PBL, 2015).

Future land-use developments can vary in magnitude, and constrain infrastructure asset systems, by limiting the possibilities for expansion. Urbanization will cause (limited) city growth, and thereby limit available space for infrastructure asset systems. In a high urbanization scenario, more people will move towards the cities. These people will require more housing, businesses, and other facilities. This will decrease the amount of available land for the expansion of infrastructure asset systems. The high urbanization scenario corresponds with an increasing immigration rate and a moderate emigration rate (Gemeente Amsterdam, 2011; United Nations, 2014b). In a medium urbanization scenario, people move towards cities, but emigration levels cause the total amount of city population to remain equal (Amsterdam, 2011). In a low urbanization scenario, people still move towards cities, but immigration remains limited. This will mainly be caused by an increasing emigration rate: cities become too crowded, and people move away (Amsterdam, 2011). Preserving nature areas may become more important in the future, and thereby limit the available space for infrastructure asset systems. The growing importance of nature preservation might cause nature areas to be preserved, and new nature areas to be developed (Provincie Noord Holland, 2016).

Uncertainties resulting from climate, innovation, population, economy, and land use developments were chosen since they have large effects on the case study. Uncertainties generated implicitly by the model are taken into account as well. These uncertainties mainly result from the complex behaviour of infrastructure asset systems, and the policies applied to them. This will be explained in part 3 & 4. It is assumed that all the applied uncertainties are sufficient to represent the future uncertainties subjected to the case study. Other (exogenous) uncertainties were excluded from this research analysis because of time constraints, and limited computational power during simulations.

2.3.3 SCENARIOS

In order to develop adaptation pathways, and thereby visualise the adaptability of the long-term planning of large intervention decisions, scenario packages were developed. The future uncertainties mentioned in §2.3.2 were summarised, and grouped into the scenario packages presented in table 1. These scenario packages will be subjected to the case study, and will be analysed during the development of the adaptation pathways, and the ESDMA analysis (part 4). The large intervention decisions that are most robust, given those scenario packages, will be found during the forming of the adaptation pathways.

Table 1. Scenario packages of future uncertain developments
The future uncertain developments (listed on the left) are divided in a medium, low, and hard scenario package.

	Medium	Low	Hard
Climate[1]	Medium Climate (G_H)	Low Climate (G_L)	High Climate (W_L, W_H)
Innovation[2]	Medium Innovation	Low Innovation	High Innovation
Population[3]	Medium Population	Low Population	High Population
Economy[4]	Medium Economy	Low Economy	High Economy
Land-Use[5]	Medium Urbanization	Low Urbanization	High Urbanization

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[1] (IPCC, 2014; KNMI, 2015)

[2] Estimated by authors

[3] (Stoeldraijer et al., 2016)

[4] (CPB/PBL, 2015)

[5] (Gemeente Amsterdam, 2011; United Nations, 2014a)

The future uncertainties are grouped into scenario packages, which were formed using scenario development predictions from the Delta-Commission and the WLO. Both development reports combine scenarios using causal relations. These relations were used to form a low, medium and hard future environment for the infrastructure asset systems.

The scenario packages are partly based on the scenarios of the Delta-Commission (Ministry of Infrastructure and the Environment, 2011). The Delta-commission combines climate scenarios with socio-economic scenarios by performing a causal effect analysis (KNMI, 2015; CPB/PBL, 2015). In this analysis low and high climate change scenarios are combined with respectively low and high population, urbanisation and economy scenarios (Ministry of Infrastructure and the Environment, 2011). This results from the fact that climate change impacts are more, and less severe in respectively large and low economic, population, and urbanisation scenarios. This is due to the importance and the density of the impact areas (Ministry of Infrastructure and the Environment, 2011).

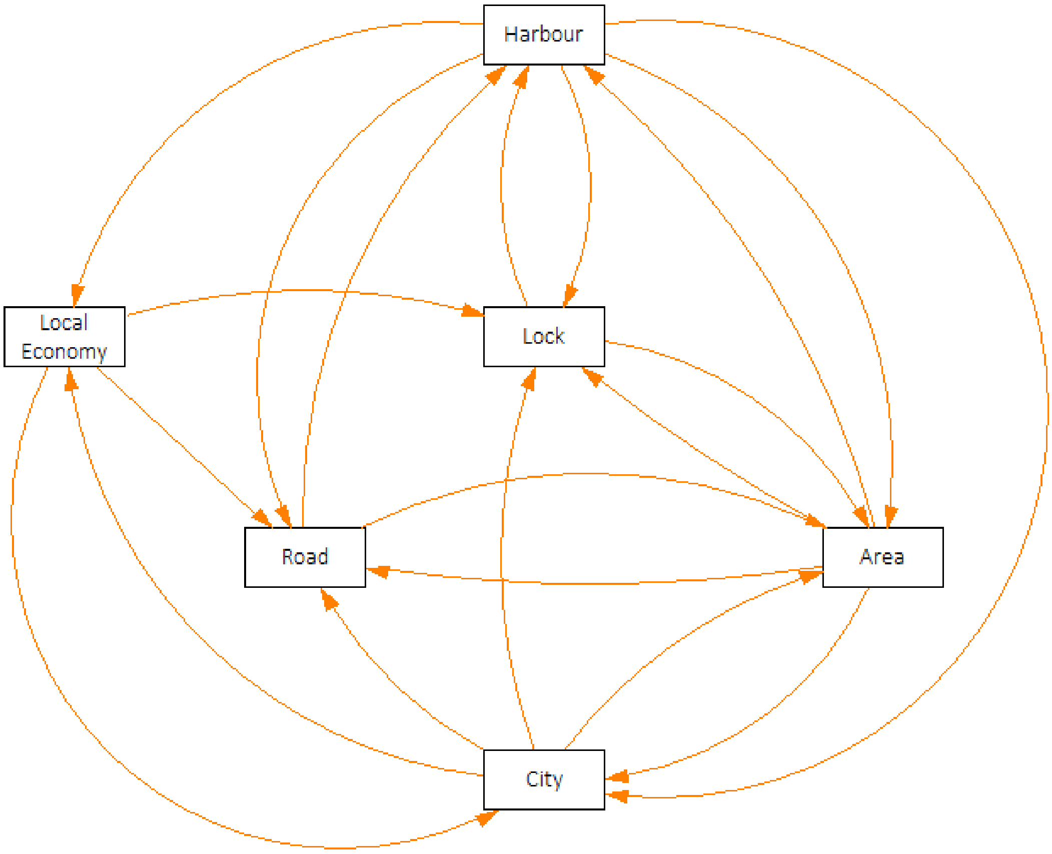
Furthermore, the scenario packages are partly based on the scenario development of the WLO (CPB/PBL, 2015). According to their line of reasoning large and low economic scenarios can only occur in respectively large and low population and urbanisation scenarios (due to the amount of labour population and consumers)(CPB/PBL, 2015) . Moreover, (technical) innovations can cause large economic scenarios, while a lack of (technical) innovation can be the main cause for a limited economic growth scenario (CPB/PBL, 2015).

By following these scenario development predictions, the hard scenario package will consist of large effects (high economic growth, high innovation levels etc.). The low scenario package will consist of low effects, and the medium package of medium effects.

In all scenario packages a future with and without the preservation of nature is used. In low scenarios more nature could be preserved since there is lower necessity to destroy nature, and build facilities (houses, businesses etc.). However, climate change would be less noticeable causing the importance of nature preservation to diminish. In hard scenarios the necessity to destroy nature for facilities could be larger. Furthermore, climate change effects could be larger, and thereby increase the importance of nature preservation.

PART 3 – MODEL BUILDING

'Models are only as good as the message that represents them' (Auping, 2017)



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3.1 INTRODUCTION PART 3

To analyse the infrastructure asset systems under future uncertain developments, a computational model was built. The model was built and the sub-models were connected with the System Dynamics (SD) method, and simulated under uncertainty with the Exploratory Modelling and Analysis (EMA) method. This is extensively discussed in section 2.2. The uncertain variables including the bandwidths used for simulating the model can be found in appendix B.

This chapter discusses the overall model conceptualisation, and will present a sector diagram in order to provide an overview of the overall model, after which the key performance indicators of the model will be listed. Sections 3.2 to 3.7 will present each sub-model separately, and includes a model formulation and validation. Finally, the verification and validation, and the experimental setup of the model will be explained. A repository with the overall model can be found on GitHub (https://github.com/MHavelaar/ThesisIAM).

3.1.1 OVERALL MODEL

An overall model was constructed to schematically represent a simplification of the city of Amsterdam with its interconnected infrastructure asset systems. This model consists out of six sub-models, which are connected, and thereby influence each other. Some sub-models are relatively fast and simple models. This is motivated by the fact that for successful use of the adaptation pathways approach, there is a need to explore a wide variety of uncertain futures and actions (Haasnoot et al., 2013). The six sub-models are dynamic and contain the:

1. City model representing the city of Amsterdam with a city population, houses and businesses;
2. Harbour model representing the Port of Amsterdam with its distribution flows to, and from the asset systems;
3. Area model representing the dynamically changing area usage of the city of Amsterdam and its asset systems;
4. Economy model representing the local economy of Amsterdam;
5. Road model representing the major road network around Amsterdam, including main distribution routes from the harbour;
6. Lock model representing the lock complex of IJmuiden.

A sector diagram is presented (Figure 6) in order to provide an overview of the overall model. A sector diagram is an aggregated diagram that describes the main sub-models and their interrelations (Pruyt, 2013). A sector diagram representation is chosen in favour of a Causal Loop Diagram (CLD), because of the size and complexity of the model structure.

3.1.2 KEY PERFORMANCE INDICATORS

The future uncertainties have multiple effects on the sub-models, and these effects can cause the models to behave differently. By applying asset management policies, the models can be adapted to those future uncertainties. In order to be able to assess, which policy is most robust to future uncertainties, and performs best under a given scenario, Key Performance Indicators (KPIs) had to be formulated.

The KPIs can be divided into two categories. The first set of KPIs are subject to the infrastructure asset systems. They determine at which moment the infrastructure system performs under its required threshold (technically or functionally). This moment is called the sell-by-date. Mitigating interventions will have to be implemented in time, to ensure that the infrastructure systems have sufficient performance. The KPIs used for the infrastructure systems are the I/C factor and the sell-by-date of the secondary function. The I/C factor represent the intensity of traffic flow divided by the capacity of the asset system. If this factor grows over a certain threshold, this will result in congestions, and a decreased level of service. The sell-by-date of the secondary function is reached if either the sewage system under the road has insufficient capacity for increased maximum precipitation intensities, or when the lock retaining height is insufficient for future sea level rise. This is explained more extensively in sections 3.6 and 3.7.

The second set of KPIs are subject to the performance of the city. The proper functioning of infrastructure can affect the development and success of a city. To ensure that the interventions on the infrastructure systems are effective, they will be measured in the cities performance. The KPIs used are city population, constructed businesses, constructed houses, constructed harbour distribution capacity, total MTPA offered to the harbour, total constructed area, available area and local economic growth. This will be explained more extensively in sections 3.2 to 3.7.

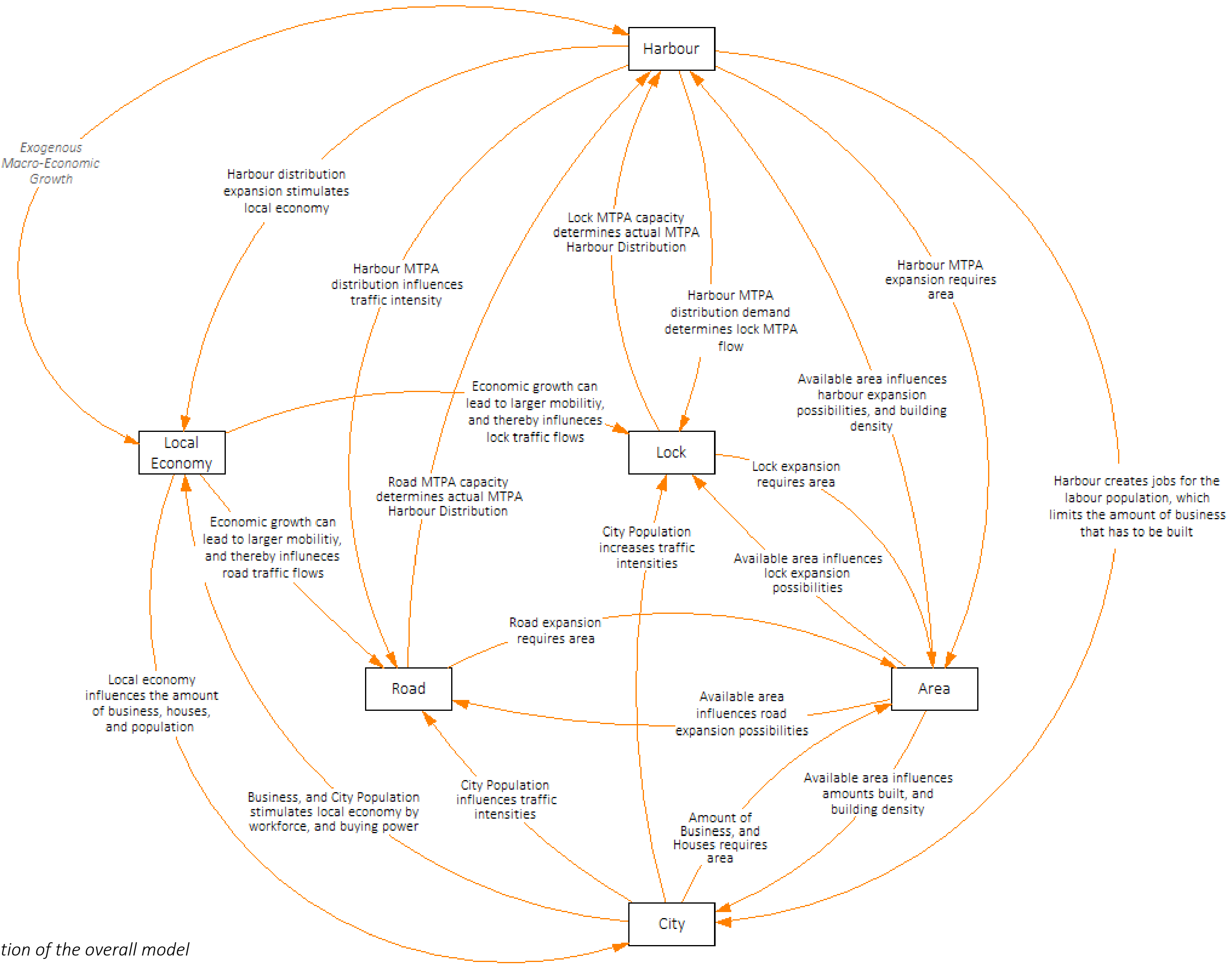

Figure 5. Sector Diagram representation of the overall model

3.2 CITY MODEL

The first sub-model used in this study is the city model. In short, this sub-model calculates the balance between the city population of the (fictional) city of Amsterdam, with the accompanied housing and businesses located in the city. The most essential elements in the sub-model are the city population, the amount of constructed houses, the amount of constructed businesses, and especially the balancing between these elements and other sub-models.

The city population is influenced by factors as immigration, emigration, deaths and births. Moreover, the city population is influenced by feedbacks with the amount of houses and with the amount of jobs. The rates for immigration, emigration, deaths and births can fluctuate over time, and thereby influence the population over time (OIS Amsterdam, 2016; Stoeldraijer et al., 2016). First, the rates can be influenced by aspects from income, lifestyle, fertility, economy, social-cultural ,and technological developments in medicine (Huizinga & Smid, 2004). Second, a well-functioning economy leads to more trust of people in a good future, and thereby causing higher birth rates (CBS, 2017a). Third, the expected obsolescence caused by the growing amount of elderly people in the population, can cause the death rate to increase. Fourth, the attractiveness of a well-functioning city, and the interconnected infrastructure can cause higher immigration and lower emigration rates.

The amount of households in a city is strongly related to the population size. The ratio of these households to the amount of constructed houses can influence the amount of immigration to the city. The lower the ratio, the more supply of houses in comparison to the demand of houses, the lower the house prices. Moreover, the more houses available, the more immigration, and vice versa (Girouard & Blöndal, 2001; Herring & Wachter, 1999; Tai, Hu, Chao, & Wang, 2017).

Within the city population, 80% can be accounted as labour population (between 15-74 years). A small percentage of this labour population does not actively want a job. In addition to the labour population that is resident in the city, a certain amount of people that is resident outside of the city, works in Amsterdam (OIS Amsterdam, 2016). The ratio of this total labour population to the amount of jobs available can influence the amount of immigration to the city. The lower the ratio, the more supply of jobs in comparison to the demand for jobs, the more immigration, and vice versa. The driver for people immigrating to the city for work predominantly results from employment opportunities, travel costs and travel time savings (Dadashpoor & Alidadi, 2017; Huang, Liu, Zhao, & Zhao, 2017).

The city population can influence the traffic intensities over the asset systems. The size of city population can influence the traffic intensities on the road and lock system. The larger the population, the more intense use of cars and leisure vessels (CPB/PBL, 2015; Gemeente Amsterdam, 2011; Wu, Li, Ding, Li, & Sun, 2017).

The constructed houses are influenced by the amount of planned houses and houses demolished. First, the amount of planned houses is influenced by the ratio of households to houses. If the ratio of households to houses increases, the house scarcity increases. This results in an increase of new planned houses, and vice versa (CPB/PBL, 2015; Gemeente Amsterdam, 2011; Huizinga & Smid, 2004).

Second, the amount of planned houses is influenced by the amount of land available for the building of new houses. If the area is very densely built, this will decrease the possibilities, and increase the cost for the planning of new houses. However, if the area is not densely built, this will decrease the attractiveness that densely built areas provided (good facilities, transportation etc.), and thereby decrease the amount of planned houses as well (CPB/PBL, 2015; United Nations, 2014b). Moreover, in highly densely built areas, the amount of land used per house decreases due to the increase of multi-storing housing (Gemeente Amsterdam, 2011).

Third, the amount of planned houses is influenced by the building policy adopted by the local government and housing developers. Local governments and housing developers can adopt a pro-active building policy. This includes planning the amount of houses according to a forecast in future population size, and thereby the amount of households requiring a house (Gemeente Amsterdam, 2011). Local governments and housing developers can also adopt a reactive policy. This includes planning the amount of houses according to the house shortage that is present in a city. With this reactive building policy, governments do not always provide sufficient building permits to diminish housing shortages before they occur (Rooijers, 2016). A contributor for a reactive building policy is that in some situations housing developers and land owners delay housing projects to increase profits (creating scarcity) (Wainwright, 2017).

The amount of houses demolished is influenced by a demolishing rate, which depends on the technical lifetime of a house. This demolishing rate can increase when there is a high vacancy degree of houses. Furthermore, the constructed houses require a certain amount of area, and thus limit the expansion of other buildings and infrastructure.

The constructed businesses are influenced by the amount of planned businesses and businesses demolished. First, the amount of planned businesses is influenced by the ratio of labour population to jobs. If the ratio of labour population to jobs increases, the scarcity of jobs increases. This results in an increase of new planned businesses, and vice versa (CPB/PBL, 2015; Gemeente Amsterdam, 2011; Huizinga & Smid, 2004). In the model, jobs are also endogenously created by the harbour according to the distribution capacity. The bigger the distribution capacity, the more jobs created (Port of Amsterdam, 2015). The amount of employees per business unit can fluctuate with economic growth, and the availability of area (Sprangers & Timmermans, 2009). The lower the economic growth, the less business will be build, the more free area, the cheaper office rents and land price, the less employees, and vice versa. Moreover, in low economic growth scenarios, only really necessary jobs will be fulfilled, which result in less employees, and vice versa. The size of the labour population actively wanting a job, can also fluctuate with economic growth. In higher economic scenarios, a higher percentage of the city population will participate in the job industry (especially woman and 50+). This also accounts for people outside of the city (Huizinga & Smid, 2004).

Second, the amount of planned businesses is influenced by the amount of land available for the construction of new businesses. Densely built areas increase the attractiveness of an area ,and thereby the amount of planned businesses, due to the accessibility of the area for clients and workers, and the possibility for people to live nearby work. If areas become to densely built, the possibilities and costs for new businesses decrease the amount of planned businesses (CPB/PBL, 2015; Gemeente Amsterdam, 2011). Moreover, in highly dense built areas, the amount of land used per business decreases due to the increase of multi-storing buildings (Gemeente Amsterdam, 2011).

Third, the amount of business buildings planned is influenced by the building policy adopted by the local government and business developers. Local governments and business developers can adopt a pro-active building policy, which includes planning the amount of businesses according to a forecast in future labour population, and the required amount of jobs. Governments can create business areas, and as such make attractive propositions for new businesses, as was done with the Zuid-As in Amsterdam (Gemeente Amsterdam, 2011). Local governments and business developers can also adopt a reactive building policy, because they cannot always adequately predict future shortages of jobs or do not possess the means to minimize future shortage of jobs.

The constructed businesses have a feedback with the local economic growth. The higher the local economic growth, the more opportunities for profitable businesses, the more business planned (CPB/PBL, 2015; Gemeente Amsterdam, 2011; Huizinga & Smid, 2004). Moreover, more businesses in an area means better development of an area, causing higher local economic growth (CPB/PBL, 2015; Gemeente Amsterdam, 2011; Huizinga & Smid, 2004).

The amount of businesses demolished is influenced by a demolishing rate, which depends on the technical lifetime of the businesses buildings. This demolishing rate can increase when there is a high vacancy degree of businesses. Furthermore, as with the constructed houses, the amount of constructed businesses require a certain amount of area, and can thereby limit the expansion of other buildings and infrastructure.

3.3 HARBOUR MODEL

The second sub-model used in this study is the harbour model. In short, this sub-model dynamically balances the distribution capacity of the harbour, and the demand in world offer over the infrastructure asset systems (in Million Tonnage Per Annum, MTPA). The most essential elements in the sub-model are the constructed harbour distribution capacity, the total MTPA offered to the harbour, and especially the balancing between these elements and other sub-models.

The constructed harbour distribution capacity is influenced over time by the amount of new harbour distribution capacity planned, and the demolition of existing harbour area. First, the amount of new harbour distribution capacity planned is influenced by the ratio of the world offer to the harbour distribution capacity. If the ratio increases, the scarcity of harbour distribution capacity increases. This results in an increase of new planned harbour capacity, and vice versa (Port of Amsterdam, 2015).

Second, the amount of new harbour distribution capacity planned is influenced by the amount of land available for the building of new harbour area. If the area is very densely built, this will decrease the possibilities for expansion, and increase the cost for the planning of new harbour area. In less densely built areas the attractiveness of good infrastructure and facilities is decreased. This results in a decrease of planned harbour distribution capacity (Decisio & Urhahn Urban Design, 2013; Port of Amsterdam, 2015). Depending on the innovation scenario, the area used for distributing one MTPA can fluctuate, the more innovation, the less area is required for distribution (Decisio & Urhahn Urban Design, 2013; Port of Amsterdam, 2015).

Third, the amount of new harbour distribution capacity planned is influenced by the building policy adopted by the port authority. Port authorities can adopt a pro-active building policy, in which the amount of new harbour distribution capacity is planned according to a forecast in future world offer. The required distribution capacity is thereby planned beforehand. In some cases, infrastructure networks are created together with the new harbour area, to ensure the proper functioning of the harbour. Large vessels can harbour the port in the future, and cargo can be transported efficiently to the hinterland. Examples are the new lock of IJmuiden and Maasvlakte 2 (CPB et al., 2001; Decisio & Urhahn Urban Design, 2013; Port of Amsterdam, 2015). Port authorities can also adopt a reactive building policy, which includes the planning of the amount of new harbour distribution according to the present shortage in distribution capacity. This is done because they cannot always adequately predict future shortages or do not possess the means to minimise future shortage. The amount of harbour demolished is influenced by a demolishing rate, which depends on the technical lifetime of the harbour buildings and distribution systems.

The total MTPA offered to the harbour (world offer) is influenced over time, and influences the harbour distribution capacity. The world offer is mainly influenced by macro-economic growth (Decisio & Urhahn Urban Design, 2013; Port of Amsterdam, 2015). Moreover, the world offer can be limited by the distribution capacity of the connected infrastructure asset systems. If these connected infrastructure asset systems have insufficient distribution capacity, some of the world offer will diverge to different harbours (Decisio & Urhahn Urban Design, 2013; Port of Amsterdam, 2015).

3.4 AREA MODEL

The third sub-model used in this study is the area model. In short, this sub-model calculates the balance between the available area for construction, and the already constructed area. The available area can limit the growth of other sub-models. The most essential elements in the sub-model are the total constructed area, the available area, and especially the balancing between these elements and other sub-models.

The total constructed area dynamically balances the available area in the overall model. Together, they have feedbacks with the city, harbour, road and lock sub-model. The total constructed area can expand by the planning of new constructed area, and thereby decrease the available area. New constructed area can be planned, and thereby reserved, for the expansion of the city and its connected infrastructure asset systems. In order to facilitate the dynamically changing city population, housing area can be reserved to accommodate future changes in amounts of households (Gemeente Amsterdam, 2011; Stuurgroep Visie Noordzeekanaalgebied, 2013). To enable harbour expansion, area needs to be reserved to make the expansion of the harbour possible (Decisio & Urhahn Urban Design, 2013). To dissolve bottlenecks in the road network, and thereby create accessibility of business and living areas, sufficient space needs to preserved for road expansions (Ministerie van Infrastructuur en Milieu, 2017). Lock expansions are required to enable the continuous growth of the harbour, and thereby safeguard the economic competitive position of the Port of Amsterdam (Rijkswaterstaat, 2012a).

The total constructed area can decrease by the demolition of already constructed area, and thereby increase the available area. Already constructed area can be demolished when the technical lifetime of a structure ends, or when structures are not in use for an extensive period of time.

The total constructed area and available area, influence other sub-models by limiting expansion possibilities. Other sub-models reserve area in the area sub-model, whilst the amount of available area can limit the possibility of expansion for other sub models. Area that is reserved for facilitating urbanization and population growth is a bottleneck for infrastructure expansions (Ministerie van Infrastructuur en Milieu, 2017). Area reserved by the harbour can limit expansion possibilities for the city and its infrastructure (Stuurgroep Visie Noordzeekanaalgebied, 2013). Finally, area can be excluded for use because of nature preservation (PBL, 2012).

3.5 ECONOMY MODEL

The fourth sub-model used in this study is the economy model. In short, this sub-model calculates the local economic growth for the entire city including the harbour. The most essential element in this sub-model is the local economic growth, and especially the balancing between this element and other sub-models.

The local economic growth is influenced by the macroeconomic growth, the amount of job spending, the harbour growth and business growth. The relative growth of one of these elements increases its importance and influence in the local economy. Macroeconomic growth considers an economy as a whole (national scale). The growth is strongly dependent on economic growth scenarios, which stipulates its magnitude on the local economy (CPB/PBL, 2015). The amount of job spending is dependent on the amount of labour population that is fulfilling a job. The more population fulfilling a job, the higher the amount of job spending, the more positive contribution to the local economy (CPB/PBL, 2015; Huizinga & Smid, 2004). The harbour growth and business growth can influence the local economic growth due to the fact that local economic growth is dependent on the production of goods and services by businesses (Kryeziu, 2016). Moreover, harbours can be the main driver for a local economy. Currently, the port of Amsterdam is the secondary driver of the Amsterdam local region (next to normal businesses) (Port of Amsterdam, 2015). Finally, local industries (harbour and businesses) can boost the local economic growth even more than macro growth (CBS, 2017b; Jonkers, 2017).

The local economic growth influences the traffic intensities over the asset systems, and causes changes in land usage. Local economic growth can lead to a larger mobility, and thereby change traffic intensities of the asset systems (CPB/PBL, 2015). Furthermore, local economic growth can lead to changes in land usage. To facilitate economic growth, land needs to be reserved. This can be seen when a harbour wants to expand, and requires more area (CPB/PBL, 2015; Stuurgroep Visie Noordzeekanaalgebied, 2013).

3.6 ROAD SYSTEM MODEL

The fifth sub-model used in this study is the road system model. The sub-model is two-handed. It calculates the proportion of the flow intensity to the capacity of the road network, and it calculates the sell-by-date of the sewer network underneath the road. It is thereby a sub-model which determines the functional, technical ,and multifunctional intervention threshold of the road system in a specific intervention policy. Therefore, the most essential elements in the sub-model are the sell-by-date of the road system policy, the sell-by-date for the sewer system, and especially the balancing between these elements and other sub-models.

The sell-by-date of the road system intervention policy is determined on basis of the I/C factor, which is a key performance indicator for intervention policies regarding the capacity of the road network, in time dependent intensity conditions. The I/C factor is an important indicator because of its generic calculation approach, and good indication of road network performances (Rijkswaterstaat, 2015a). The I/C factor is calculated by the relation between intensity (I) over capacity (C). Capacity and intensity can be calculated by the amount of PCE (Person Car Equivalent) or MVT (motorverhicles). The relation between both is the amount of trucks, and the fraction of trucks to cars (Rijkswaterstaat, 2015a; Appendix E.3, Interview Antea Group). Interventions on performances of road networks are required when the I/C factor is above its threshold. Newly built networks are designed with an I/C factor of maximum 0.8 (Rijkswaterstaat, 2015b). The threshold for road intervention is when the I/C factor is above 0.8. Above this threshold the bad road performance leads to a vast decline in level of service. The chance of congestion within 30 minutes is <<1% when the I/C factor is in between 0.3 and 0.8, <20% when the I/C factor is in between 0.8 and 0.9, 20-100% when the I/C factor is in between 0.9 and 1.0 and 100% when the I/C factor is above 1.0 (Rijkswaterstaat, 2015a).

The capacity of the road network is calculated by an initial value which is influenced by factors that in- or decrease the capacity. The capacity is increased by constructed road capacity and renovations during intervention moments. The capacity is decreased by deterioration and other side effects, and diminished road capacity. The initial value of the road capacity is translated from the current road network around the city of Amsterdam, with each their specific capacities due to number of lanes and maximum speeds. The current road network around the city of Amsterdam integrated in the sub-model consist of the ring A10 and parts of the A8, A5, A4 ,and A2 (Rijkswaterstaat, 2017c).

Constructed road capacity can increase road capacity by constructing new road lanes. Addition of lanes can solve congestion problems and improves quality of infrastructure (Rijkswaterstaat, 2017b), but could also lead to attraction of new traffic and thereby cause new congestion, safety ,and environmental problems (CPB/PBL, 2016). In road intervention policies, intervention often takes place on the weakest links (A10 West, (Rijkswaterstaat, 2017a). Interventions on the weakest links of the road network could have influences within the whole network. In road planning it is thereby recommended to consider the road as a part of a network, and apply a network approach (Arts, 2007; Rijkswaterstaat, 2015a; Appendix E.3, Interview Antea Group). Planning and construction times are of great importance for effective road intervention projects. Long planning periods can cause a longer period of congestion, and the resulting loss in travel times. Planning periods for large road interventions are usually between 5 to 20 years. This long periods are mainly caused by the multiple side effects of new roads, amount of available space for road expansion projects, the multiple parties involved in a road project, and the growing influence of the law (Arts, 2007). Innovations, like ITS (Intelligent Traffic Systems) and AD (Automated Driving) are using the available road space efficiently, so that a larger amount of capacity can be entailed (50% less congestion). Innovations are thereby able to increase the road capacity, but can also attract more road traffic (Milakis et al., 2017).

Deterioration and other side effects can decrease capacity, but can be partly or completely restored during renovation moments. The road quality is decreasing during its lifetime (Figure 7). Regular maintenance can be performed in order to restore the quality of the road, but the quality will never be as good as it was before (capacity is lost). When the road quality is below its intervention threshold, large interventions like renovations or replacements are required, the road quality and capacity is then restored to its initial value. The intervention threshold is the minimum quality a road needs to have in order to fulfil its function, plus a safety margin (CPB/PBL, 2016) .

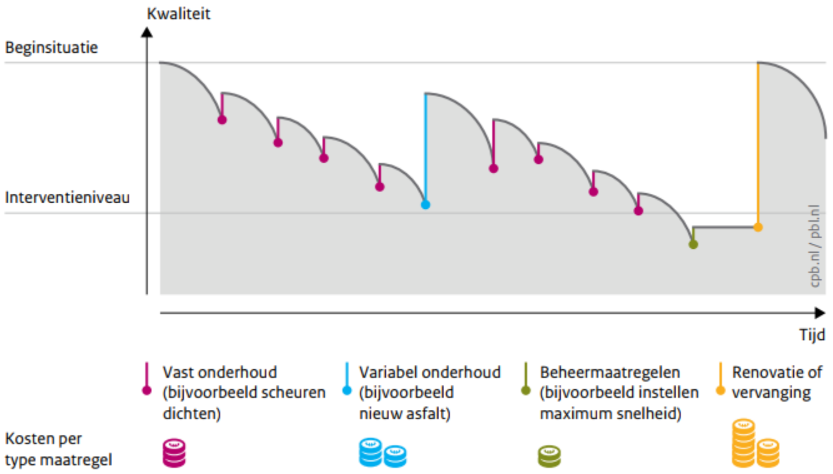

Figure 6. Road quality development, including maintenance interventions during the lifecycle of a road
Regular maintenance (purple) cannot restore the road quality to its initial level, variable maintenance interventions (light blue) can restore quality, but only extend lifetime of the road system, large interventions (yellow) area required to restore the road quality to its initial level (CPB/PBL, 2016)

Road maintenance is usage dependent. The more a road is used, the faster the deterioration. The most important factors in this case are the amount of traffic that uses the road and the weight of that traffic. The intensity, and especially the amount of trucks are causing faster deterioration (Essen, Boon, Koetse, & Bruinsma, 2004). Climate change can increase the deterioration of a road, the main causes are the instability of road foundations due to rainfall, the more salt intrusion due to colder winters, and the more deformation of asphalt due to high temperatures during summer (Ooststroom et al., 2008).

Climate change can decrease the overall capacity of a road, because of extreme weather events. Flooding events, erosion of road embankments, heavy rainfall and snow could lead to a periodic decrease of achievable road capacity. The more extreme weather events, the less overall achievable road capacity (Bles et al., 2015).

Diminishing of road lanes can decrease capacity, the capacity is restored when the road lanes are renovated. Currently (2017), an intervention project is planned to renovate the A10, during renovation these 'weakest link' have to be closed, and capacity is lost during the renovation period. After renovation, the road lanes are reopened, and the capacity is restored to its initial level (Rijkswaterstaat, 2015a, 2017a). Climate change can cause the intervention moment to be earlier than originally planned, because of the faster deterioration of the road (Ooststroom et al., 2008). Innovative measures can cause the intervention moments to be later than originally planned, because of lifetime extending measures. For example, LEAB asphalt layer decreases deterioration rate, and thereby extends lifetime of asphalt layer (Rijkswaterstaat, 2016a). Furthermore, lifecycle extending remedies can extend the lifecycle of the road with three years (Rijkswaterstaat, 2016a).

The intensity conditions are determined by car-, and truck intensities during rush-hour (peak intensities). Car intensities during rush-hour are influenced by labour population, city population and local economic growth. A changing city population can lead to a change in the development of car intensities in the road network (Gemeente Amsterdam, 2011; Ministerie van Infrastructuur en Milieu, 2017; Wu et al., 2017). Economic growth can cause more jobs, more people take the car to work, and thereby increase traffic intensities (Wester, 2016). Car possession of people can vary due to climate change policies (reduce CO_2), economic growth, population developments and car possession of people living in cities (CPB/PBL, 2015).

Truck intensities during rush-hour are influenced by the amount of distribution through the harbour. Developments in harbour distribution, and thereby, the amount of trucks, and especially the amount of tonnage per truck can influence road intensities (CPB/PBL, 2015). The harbour distributes its goods via the connecting assets, as the road, rail and waterway (Port of Amsterdam, 2015). The mix between cars and trucks on a road is influencing the road capacity. Trucks are requiring more space, and have other speed limits than cars. The more trucks, the less the capacity of a road. This effect is calculated in the relation between PCE and MVT (Rijkswaterstaat, 2015a).

Congestion leads to less capacity, as a consequence people and goods can diverge to a change of transport type. Congested roads lead to divergence of people to other transport types, as the train, bus, metro and bicycle (Ministerie van Infrastructuur en Milieu, 2017). Congested roads lead to divergence of goods to other transport types, as the rail and the waterway (Ministerie van Infrastructuur en Milieu, 2017).

The sell-by-date for the sewer system is a key performance indicator for determining the multifunctional lifetime of the road system. The sewer system is of importance for the road system, because it drains rain water from the road surface. Rain water, which cannot be drained by the sewer system, can cause road surfaces to flood, and increases of groundwater levels that causes uplifting of the road. Both effects lead to a lower quality, and thereby capacity of the road (Bles et al., 2015). Extreme weather events, can cause tunnel systems to overflow. The road system is temporary unavailable, and the access to the area is disabled. Extreme weather events thereby lead to an increase of travel times for the road network (Bles et al., 2015; Huibregtse, Napoles, Hellebrandt, Paprotny, & Wit, 2016). The probability of a certain scenario regarding climate change, and the consequence in terms of the required level of service of the road system, determines the intervention moment for the sewer system (Bles, 2014; Bles et al., 2015; Huibregtse et al., 2016).

Timely planning of interventions, on the sewer system is of importance for the multifunctional performance of the road system. A lack of intervention, or a delayed intervention on the sewer system leads to a loss in performance, and level of service for the road system (Huibregtse et al., 2016). Intervention moments need to be determined for the connected asset systems, as an asset is not functioning individually.
A sewer system and a road are highly connected, and intervention moments need to be adequately planned in order to reach maximum efficiency in terms of costs, risk and performance (Alegre & Coelho, 2012). Currently (2017), at the intervention on the A10, the drainage system is renovated during maintenance moment of road (Rijkswaterstaat, 2017a) .

The sell-by-dates of the road system policy and the sewer system are balancing between other sub-models. The city population influences traffic intensities on the road. A high quality of the road infrastructure influences attractiveness of the area, and thereby increases the city population (CPB/PBL, 2015; Wu et al., 2017).

The harbour distribution influences the amount of trucks over the road. The achievable distribution of the harbour is dependent on the road capacity (Port of Amsterdam, 2015). Expansion of the road infrastructure requires area, timely planning is recommend in order to reserve area, which can be reserved by other assets or the city otherwise. Moreover, the amount of available area limits road expansion possibilities (Ministerie van Infrastructuur en Milieu, 2017). The quality of the road infrastructure, and amount of lost vehicle hours due to congestions is of high importance to the local economy. Furthermore, economic growth increases the traffic intensities on the road system (CPB/PBL, 2015; Wester, 2016).

3.7 LOCK MODEL

The sixth sub-model used in this study is the lock model. This sub-model has two main purposes. It calculates the available capacity of the lock system in comparison to the intensity of commercial and leisure vessel flows. Moreover, it dynamically calculates if the retaining heights of the lock system are sufficient for extreme peak heights in sea level. For both purposes, the model presents sell-by-dates, at which interventions have to be taken to ensure the functionality of the system. The model is thereby able to determine the functional, technical and multifunctional performance of the lock system for a specific intervention policy.

The first essential element causing a sell-by-date is the intensity/capacity (I/C) factor of the system. The balancing of this factor, and the influence it has with other sub-models is of great importance. The I/C factor of a lock system is one of the major key performance indicators for the proper functioning of the system. The official design guidelines for locks and waterways state that a study has to be started for the expansion of a lock system when an I/C factor of 0.5 is reached. If the I/C factor reaches 0.6, average waiting times for vessels will increase exponentially. This point is considered as the bottleneck for the system (Rijkswaterstaat, 2011). The waiting times are presented in underlying Figure 8.

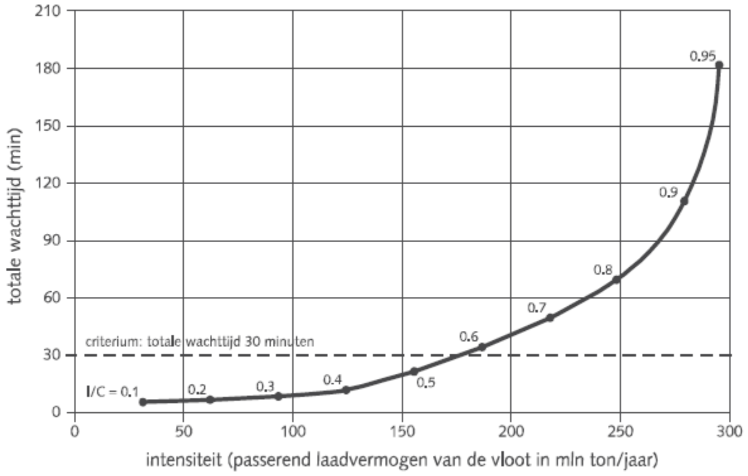

Figure 7. Waiting times at locks as a function of intensity, including I/C factors (example: Kreekraksluis) (Rijkswaterstaat, 2011)

The I/C factor is calculated by dividing the intensity of vessel flow through the lock, by the available capacity of the lock, in million tons per annum (MTPA). The capacity of the lock has an initial value, and is influenced by the new planned lock capacity, the cumulative deteriorated lock capacity and the demolished lock capacity. Initially, the lock system consists out of four different locks with each there own specific capacity (Rijkswaterstaat, 2014b; Royal Haskoning DHV, 2014). The Noordersluis, Middensluis, Zuidersluis and Kleine Sluis (Rijkswaterstaat, 2014b; Royal Haskoning DHV, 2014).

To increase the capacity of the lock system, new locks can be planned. Currently, a new sea lock is constructed, which is expected to open in 2019. This will be the biggest sea lock in the world (Blokland, 2015). The Noordersluis will reach its end of technical lifetime in approximately 2030, and can be renovated and reopened for use (Rijkswaterstaat, 2014b; Royal Haskoning DHV, 2014). Furthermore, additional new locks can be constructed at the IJmuiden location (Appendix E.6, interview BAM PPP). A copy of the new sea lock can be constructed, which can save construction time, planning time and costs from the already gained experience (Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP). Depending on innovations in the future, bigger and more efficient sea locks could be constructed. Innovative locks could possibly lead to longer planning times, construction times and costs due to a lack of experience.

An innovative lock can create scaling benefits due to faster lock cycles, and provide safe passage to even larger vessels (Royal Haskoning DHV, 2014; Appendix E.6, interview BAM PPP). An example of an innovative lock is the gel lock; a lock without doors but with a huge amount of gel through which vessels are pulled through. This can lead to smaller waiting times and less salt intrusion (Sandt, 2011). Faster lock cycles can also be achieved with innovative doors and pumping mechanisms (Rigo & Daniel, 2010). A bubble screen and/or back pumping station can be implemented to prevent salt intrusion (Appendix E.6, interview BAM PPP).

The planning of new locks has to be initiated in time, and has to take delays in planning and construction time into account. If new lock projects are delayed this can result in congestion problems, and thereby high waiting times. An example can be taken from the new sea lock currently constructed at IJmuiden. A study of the entire area was conducted between 1999 and 2010. After the study was finished, the planning was initiated, which together with the construction will take an additional 9 years (if no delays occur). The I/C factor has been over its threshold for some years, and waiting times are increasing yearly (Rijkswaterstaat, 2016b).

In normal conditions (design conditions), a lock system has a certain deterioration rate. This deterioration can be maintained during, preventive and corrective maintenance moments. Preventive and condition based interventions include cleaning, inspections, tests and small maintenance works (Glerum & Vrijburcht, 2000). Corrective interventions include urgent failures that cause unsafe situations, and/or immediate unavailability, for example doors that are not opening or closing, or visual and communication system failures (Glerum & Vrijburcht, 2000). Renovations and replacements include the replacement of doors, and the replacement of other major electrical/mechanical parts (Glerum & Vrijburcht, 2000).

In abnormal conditions, the deterioration of a lock system can be accelerated. If I/C factors rise beyond there threshold the lock system will have to work above its design parameters. Especially in the months where the highest flows of commercial and leisure vessels coincide (summer months). This causes faster deterioration, more failures, and congestions (Rijkswaterstaat, 2011). Climate change can increase the deterioration of the lock system, and change the overall capacity of the lock system due to extreme weather events. Extreme warmth can cause clamping of doors (Ooststroom et al., 2008), extreme water levels can cause faster deterioration of pumps (Rijkswaterstaat, 2014c), and sea level rise can cause waves with bigger forces on the construction (Broos et al., 2012). Extreme weather events can decrease the locks overall capacity. During extreme water levels, it is impossible to perform a lock cycle (Rijkswaterstaat, 2011). Furthermore, extreme winds, crosswinds and low visibility make lock passage impossible (Glerum & Vrijburcht, 2000).

Locks can be demolished, or be put out of order, after their technical lifetime is reached. This moment is reached when the parts that are hard to maintain require replacement, or replacement can no longer guarantee there function (chambers, lock heads, fixed bridges). The technical design lifetime of a lock is normally 100 years. The end of technical life can be accelerated by climate change. Forces different from the design parameters can accelerate the end technical lifetime, which causes faster deterioration (Rijkswaterstaat, 2014c).

Innovative measures can cause the intervention moments to be later than originally planned, because of lifetime extending measures. Examples are probabilistic calculation methods for improving the judgement of the 'safe' remaining technical lifetime (Deltares, 2015). Improved measuring tools for measuring degradation of materials can increase the technical lifetime by increasing the precision of anticipation measurements (Deltares, 2015). The use of modern synthetic materials and composites can decrease contact wear and corrosion (Rigo & Daniel, 2010).

The intensity of vessel flow through the lock is influenced by the world offer for commercial vessels, and the offer for leisure vessels passing through the lock. The world offer for commercial vessels is influenced by the harbour demand, the waiting times at the lock, and scaling benefits due the increase in lock size. The harbour has a certain offer from sea going vessels, mostly influenced by macro-economic growth (Port of Amsterdam, 2015; Stuurgroep Visie Noordzeekanaalgebied, 2013). If the I/C factor of the lock rises above this threshold, the waiting times can increase exponentially, and vessels will diverge to Hamburg, Rotterdam or Antwerp (Port of Amsterdam, 2015; Rijkswaterstaat, 2011, 2012b). Momentarily, the offer to the port of Amsterdam is limited due to the insufficient dimensions of the biggest lock at the IJmuiden complex (Noordersluis). Larger lock dimensions can increase the world offer in commercial vessels, by providing safe passage to larger vessels. Moreover, vessel dimensions will probably keep increasing due to logistic innovations (larger container cranes), the widening of the Panama Canal and its locks, the widening of the Suez Canal, and the ongoing incentive of lowering transport costs.

(Port of Amsterdam, 2015; Rijkswaterstaat, 2012b; Stuurgroep Visie Noordzeekanaalgebied, 2013; Appendix E.6, interview BAM PPP). The offer for leisure vessels passing through the lock is influenced by the population size and the local economic growth. A higher population size will cause more use of leisure vessels (Rijkswaterstaat, 2012b). Moreover, higher local economic growth will cause more purchasing power for leisure vessels.

The second essential element causing a sell-by-date is the required retaining height for the lock system, when compared to the constructed retaining height. The required retaining height is influenced by the amount of sea level rise, induced by climate change. The lock system of IJmuiden is an important flood control structure in the province of North-Holland, and therefore has a required retaining height (according to the Dutch 'law for flood control structures'). The lock system of IJmuiden is a primary flood control structure, and is labelled with category b. This category includes structures that can close off sea-, and/or river arms from directly connected open water (Rijkswaterstaat, 2009, 2014a). Therefore the lock complex has a required retaining height, which can change dynamically over time due to sea level rise. In extreme climate change scenarios (WL + WH) the sea level can rise up to 120 cm in the Netherlands (KNMI, 2015, 2016). In low climate change scenarios (GL + GH) sea levels can rise up to 55 cm (KNMI, 2015, 2016).

If the required retaining height for the lock system surpasses the constructed retaining height, an intervention is required to sufficiently protect the hinterland from flooding. The required retaining height is dependent on the geographical location of the flood control structure and the structures flood protection category (in this case b). To calculate the exact retaining heights, basin capacity calculations have to be performed. Since these calculations are beyond the scope of this thesis, estimations are used from literature. The retaining height for gates is different than for the remaining structures. This is mainly due to the fact that some overtopping of the gates is allowed, and a single lock consists out of multiple gates (failure probability of multiple gates is smaller). However, overtopping is only permitted if extra measures have been taken to ensure that no undesired scouring takes place, the remaining parts of the lock are made flood proof, and the storage capacity of the connected waterways are not exceeded (Glerum & Vrijburcht, 2000). The Kleine and Zuidersluis were made completely flood proof during their last renovation. The locks (including gates) have a retaining height of NAP +8.50m (Rijkswaterstaat, 2009, 2014a). The Noordersluis and Middensluis might require an intervention due to insufficient retaining height. Newly built locks are designed to cope with future sea level rise, flexible doors are integrated that can be extended in the future (Appendix E.6, interview BAM PPP). The retaining height for the doors of the IJmuiden lock complex is NAP + 5.15 m in the year of 2017 (chance of overtopping 1:10.000) (Rijkswaterstaat, 2007; Zwan, Bezuyen, Labeur, Molenaar, & Vrijburcht, 2006). The retaining height for remaining parts of lock structure is set to NAP + 7.00 m (chance of overtopping 1:10.000) (Zwan et al., 2006). In 2100 the retaining heights for the lock gates has to be NAP +6.06 m (in a high climate change scenario) (Rijkswaterstaat, 2009, 2014a). In 2100 the retaining height for the remaining parts of the locks has to be NAP +7.91 m (in a high climate change scenario (Rijkswaterstaat, 2009, 2014a).

As explained, relatively fast and simple models are required to explore a wide variety of uncertain futures and actions. Therefore the lock sub-model limits itself by only considering its transportation function and the lock retaining height function from the sea side. The following functions were excluded:

- The locks function for transporting water to the sea through the pumping station and sluice is not taken into consideration. In reality the lock regulates the water levels of the Noordzeekanaalgebied, IJ, city waters of Amsterdam and the Amsterdam Rijnkanaal for 95% (Decisio & Urhahn Urban Design, 2013; Rijkswaterstaat, 2009, 2012c);
- The effects that climate change can have on the river side of the lock were not taken into account. Interventions due to extreme low, or high water levels could be necessary in the future (Decisio & Urhahn Urban Design, 2013; Rijkswaterstaat, 2012c);
- In reality, the amount of lock capacity is limited to a maximum amount of salt intrusion. Too much intrusion of salt water can affect drink water resources and agriculture water. The amount of salt intrusion is not taken into account (Appendix E.6, interview BAM PPP)(Rijkswaterstaat, 2008).

Furthermore, the capacity of single locks has to be calculated with extensive software for vessel flow calculations. This software was not available for this study. Therefor assumptions were made, based on literature. It is recommended to combine the ESDMA and adaptation pathways approach with input from such calculation software (section 5.2).

3.8 MODEL VERIFICATION AND VALIDATION

To ensure that the model was fit for purpose, the model was verified and validated. The model was verified with help of model debugging, testing of the numeric integration method and time step, performing a unit check and testing sub-models partially. The model was debugged by fixing the errors and warnings before simulation. As numerical integration method Euler was chosen with the smallest time step that did not show different behaviour (appendix A). A unit check was performed by checking the unit consistency of all variables. All sub-models were built separately, and tested partially (Pruyt, 2013). The results of these tests are summarised in the experimental setup (section 3.9).

The model was validated with help of sensitivity and uncertainty analysis, direct structure tests, structure-oriented behaviour tests and behaviour reproduction tests. To ensure the model was fit for purpose, the main focus was on the behaviour of the KPIs. Sensitivity and uncertainty analyses were performed in EMA, by analysing output behaviour to real system data and expert interviews. Direct structure tests in which the structure is tested without simulating the behaviour, were performed with help of expert interviews and literature. The outcomes of this test results in the structures of the sub-models as described in section 3.2 to 3.7. Structure-oriented behaviour tests were performed to test the structure indirectly, and finding errors by running the model, and comparing the behaviour to real/anticipated behaviour. The identification of influences between variables, as described in section 3.2 to 3.7, is the main result of this test. An example of the outcome of this test for an important KPI is shown in Figure 9. Behaviour reproduction tests were performed to statistically compare model output with past and future behaviour of the real system (Pruyt, 2013). An example of this tests for an important KPI can be found in Figure 8.

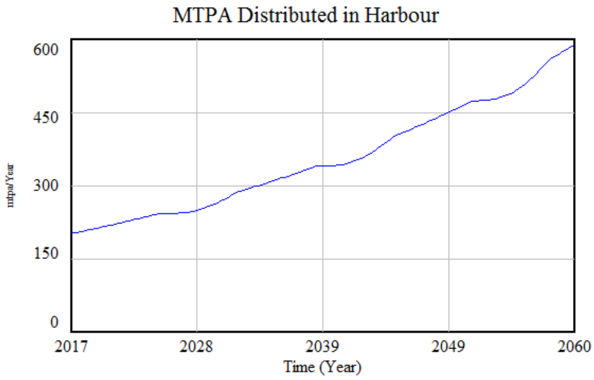

Figure 8. VENSIM graph of the MTPA distributed in the harbour of Amsterdam (high economy scenario)
It is anticipated that the amount of tonnage distributed in the harbour of Amsterdam will grow in the following years. Currently a total amount of 200 Million Tons Per Annum (MTPA) was distributed. In 2030 the harbour expects to distribute 300 MTPA (in a high economic growth scenario). Using linear extrapolation this would mean that the harbour would distribute around 600 MTPA in 2060 (Port of Amsterdam, 2015).

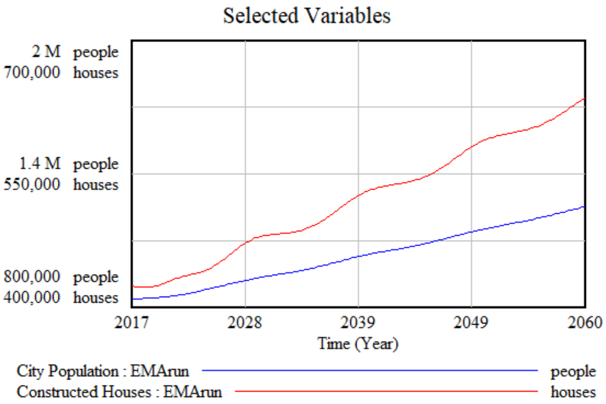

Figure 9. VENSIM graph of the city population (blue, people) and amount constructed houses (red, houses).
First, it is expected that the city population of Amsterdam will reach the 1 Million people in maximum 20 years from now (Gemeente Amsterdam, 2016). Second, it was expected that the behavior of the constructed houses was directly related to the behavior of the city population. This figure shows that this is the case (both variables use different unit scales).

3.9 EXPERIMENTAL SETUP

After the verification and validation of the model, an experimental setup was required. First, an experimental setup for the SD model is required. In order to perform simulations a numerical integration method has to be used. Since the model contains very discrete functions, Euler was used. The discrete behaviour origins from sudden interventions in the asset systems, which are not continuous over time. However, Euler can be insufficiently precise, unless a very small time step is chosen. Therefor the time step of 0.00390625 was chosen. This is the smallest step for which no changes were visible in behaviour, when compared to one time step longer (see appendix A). The simulations will be performed from 2017, until the final time of 2060. Most studies to which the model behaviour can be compared have a final time around 2060. Moreover, decision-makers don't consider decisions based on too long time horizons (Appendix E.5, Interview Rijkswaterstaat). To ensure that the time horizon was not chosen too short, a simulation was performed beyond the assumed long term time horizon. This showed that no sudden disruptions of behaviour (see appendix A; Pruyt, 2013). A full overview of the model is presented in the GitHub repository as HTML file (https://github.com/MHavelaar/ThesisIAM). The experimental setup for the SD model can be summarised as:

- VENSIM software: VENSIM® DSS for Windows Version 6.4E (x32);
- Time Unit: Year;
- Initial Time: 2017;
- Final Time: 2060;
- Time Step: 0.00390625;
- Reported Time Step (for EMA simulations): 0.25;
- Integration method: Euler.

Second, an experimental setup for the EMA simulations is required. The SD model will be loaded into the EMA workbench in which they will be simulated. All constants and variables from the model will be defined in the script used for the simulation. To ensure that all possible combinations of uncertainties are simulated, every simulation will be performed with 1000 runs in Python. This large amount runs does require a great amount of computational power in combination with a large amount of uncertainties. A maximum of 30 uncertainties can be used, before simulation times become too long. To minimize the amount of uncertainties, the majority of exogenous uncertainties as described in §2.3.2 (population, climate change, innovation etc.) will be simulated with a switch. In other words, a low, medium, or hard climate change scenario could influence multiple sub-models simultaneously, but would always be either low, medium, or hard in all sub-models (depending on the input of the switch). The remaining uncertainties which are mostly generated endogenously will be defined with a certain bandwidth. It might for example be unsure how long it will take to plan and construct a certain policy. Therefor it is given a bandwidth, which will be simulated with every combination of all other bandwidths and switches. A repository with the source code and all relevant data can be retrieved from GitHub (https://github.com/MHavelaar/ThesisIAM). The experimental setup for the EMA simulation can be summarised as:

- EMA Workbench release: 0.9.5;
- Model Uncertainties: Appendix B;
- Nr_experiments: 1000.

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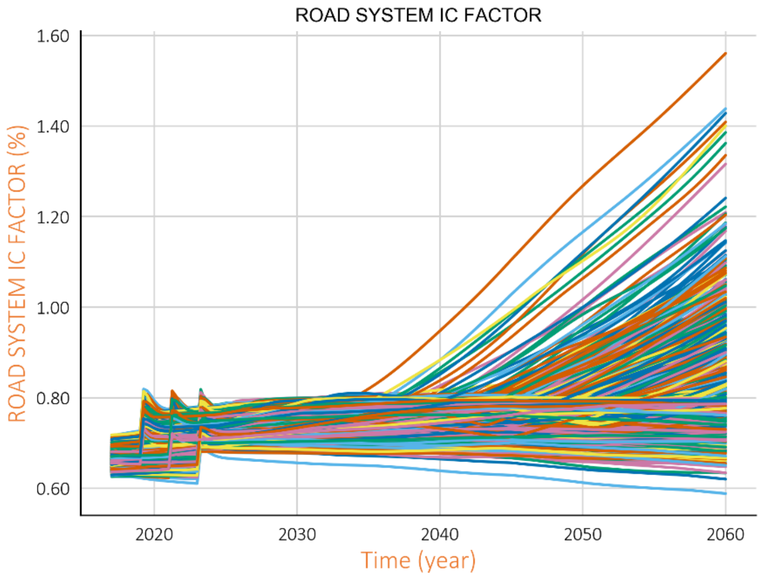
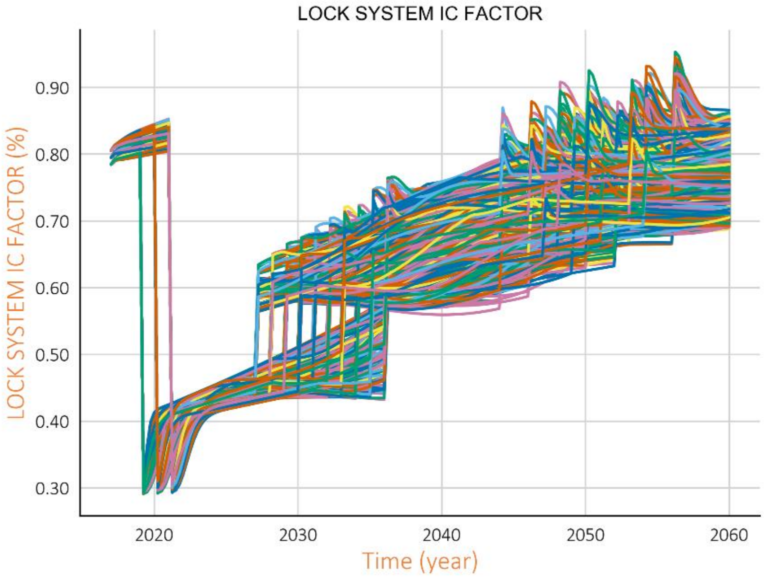
PART 4 - RESULTS





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4.1 INTRODUCTION PART 4

The scope of this chapter is limited to the main results which were found during the EMA simulations and the formation of the adaptation pathways. A repository with the source code and data used for obtaining the results can be found on GitHub (https://github.com/MHavelaar/ThesisIAM). This chapter provides insight in the statements of the hypothesis, and the research question (section 1.3 & 1.4). Section 4.2 & 4.3 discuss the extent to which the results, and thereby the proposed methodology of this study, provides insight in the dynamic uncertainties and complexities subject to infrastructure asset systems. Section 4.4 discusses to what extent the results can be used to improve large intervention decisions for complex infrastructure asset systems, subjected to dynamic uncertainty. Every section is provided with a reflection to the current practices in infrastructure asset management.

4.2 COMPLEX INFRASTRUCTURE NETWORK UNDER DYNAMIC UNCERTAINTY

In this section, the main results are presented regarding the dynamic uncertainty subjected to the complex infrastructure systems. First, the general results are described, after which examples from the case study are provided. Finally the results are reflected to the current practices in infrastructure asset management.

GENERAL RESULTS COMPLEX INFRASTRUCTURE NETWORK UNDER DYNAMIC UNCERTAINTY

When simulating the full range of uncertainties, the first observed result was that insight was created in the dynamic uncertain developments, subjected to the complex multifunctional infrastructure asset systems. The Key Performance Indicators (KPIs) on which interventions are primarily based, were presented dynamically over time, with all uncertainties incorporated for decision-making. The technical and functional performance of the infrastructure asset system in its main and secondary function can thereby be maximised.

PRIMARY FUNCTION UNDER DYNAMIC UNCERTAINTY

The technical and functional performance of the main function of the infrastructure asset systems, considered in the case study, is mainly influenced by developments in population, economy, innovation, climate, and land use.

A key performance indicator, for measuring technical and functional performance of the main transport function of a lock system is the I/C factor. As can be seen in Figure 10, the I/C factor of the lock system is mainly dependent on the amount of macro-economic growth. The increase in demand from the harbour, which is strongly related to macro-economic growth, increases the intensity of vessel flow through the lock. Moreover, it can be observed that around 2020 a decrease in I/C is present due to the opening of the new sea lock IJmuiden. The actual opening date depends on the amount of delay in construction time. Figure 11 shows an increase in I/C between 2027 and 2036, related to the end of the technical lifetime of the Noordersluis. The actual closing date, is dependent on climate change scenarios and breakthroughs in innovation. The latter being more important, since climate change effects are not so strong in the short term. Moreover, many research is currently being performed for the replacement of the majority of all wet infrastructure systems in the Netherlands (Rijkswaterstaat, 2015c).

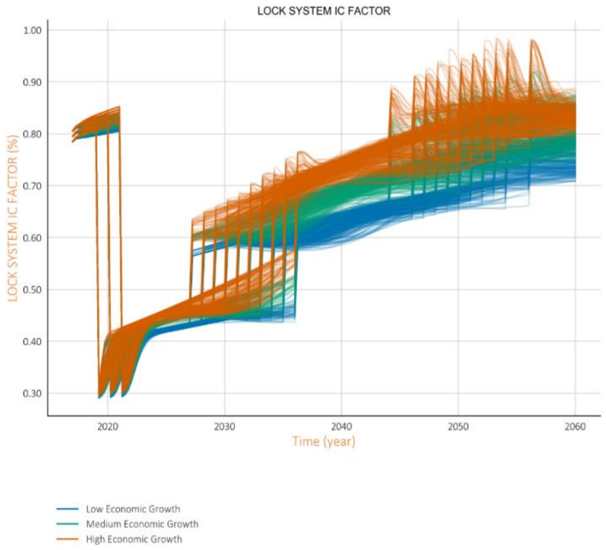

Figure 10. I/C factor of lock sorted on economy scenario

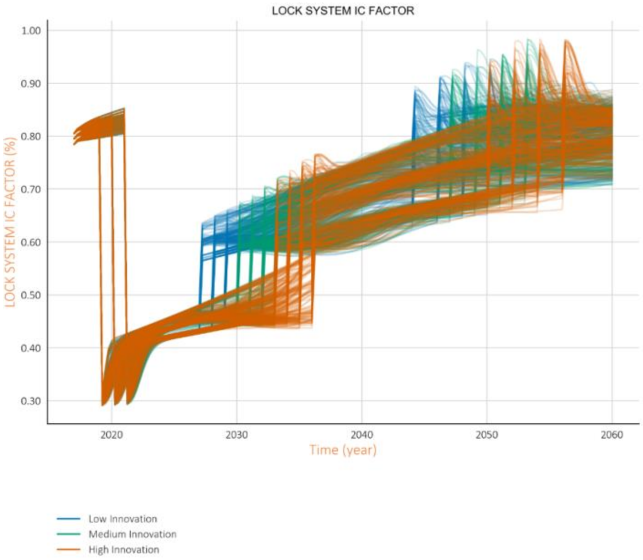

Figure 11. I/C factor of lock sorted on innovation scenario

Approximately 10-20 years later the Middensluis will have to close for the same combination of reasons. However, since climate change has stronger effects in the long term, it can be observed that high innovation scenarios hold shorter technical lifetimes than medium innovation scenarios. In other words, in the long term, climate change can have a stronger effect on the technical lifetime of locks, than innovations. Furthermore, it can be observed that after a lock closes, high I/C factors can cause vessels to diverge to different harbours due to long waiting times (after a certain time, I/C factors drop).

A key performance indicator, for measuring technical and functional performance of the main transport function of a road system is as with the lock, the I/C factor. The I/C factor of the road, is as the lock system, dependent on the demand from the harbour. The road is however, more dependent on the growth of the city population, and labour population, indicated by urbanisation (Figure 12). As is presented in Figure 12, the higher the urbanisation scenario, the bigger the chance for high traffic intensities. Peak intensities only occur in extreme scenarios and a lack of innovation. People are choosing other ways of transport in high I/C factors, but in large scenarios, population projections increase stronger than this effect. As is projected, the road network will reach its maximum capacity at about 2050. As can be observed in Figure 12, between 2018 and 2022, an increase in I/C is caused by the renovation (extension of technical lifetime) of the A10, the duration depends on the delay in construction, and planning time. The A10 will then reach its end of technical life at about 2040, the exact moment depends on the climate scenario (Figure 13). Moreover, high climate scenarios cause higher I/C values until the end of simulation, this mainly results from deterioration and sewer overflows. Innovations like ITS and automated driving are expected to have great positive effects on road capacities. The simulations showed that in the hard scenarios, innovations are necessary to prevent large capacity problems, the effect can however be limited because innovative solutions attract people to use the road network.

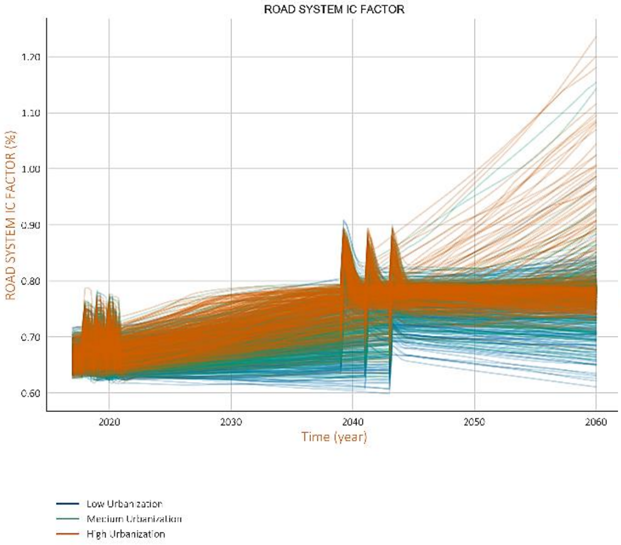

Figure 12. I/C factor of road sorted on urbanisation scenario

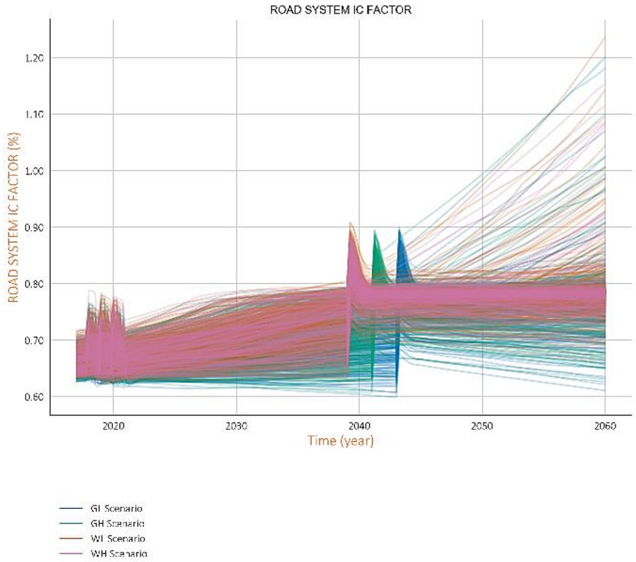

Figure 13. I/C factor of road sorted on climate scenario

SECONDARY FUNCTION UNDER DYNAMIC UNCERTAINTY

The technical and functional performance of the secondary function of the infrastructure asset systems, considered in the case study, is primarily influenced by developments in climate.

The retaining height of the lock system can become insufficient for flood protection in high climate scenarios (WL & WH scenario). The embankments in between the locks will reach their sell by date, approximately 30 years after the start of simulation (in 2046). The retaining height of the lock doors do not reach their sell-by-date, this is mainly caused by the acceptance of overtopping for lock doors. This is presented in Figure 14.

The sewer system, which is connected to the road system, reaches its sell-by-date dependent on the climate scenario. The climate scenario entails mostly the effects of flooding due to precipitation. The higher the scenario, the earlier the sell-by-date is reached. This is presented in Figure 15.

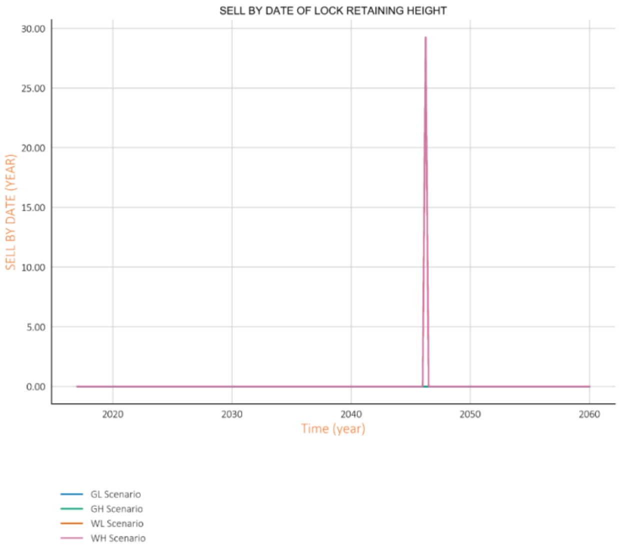

Figure 14. Sell by date retaining height lock system

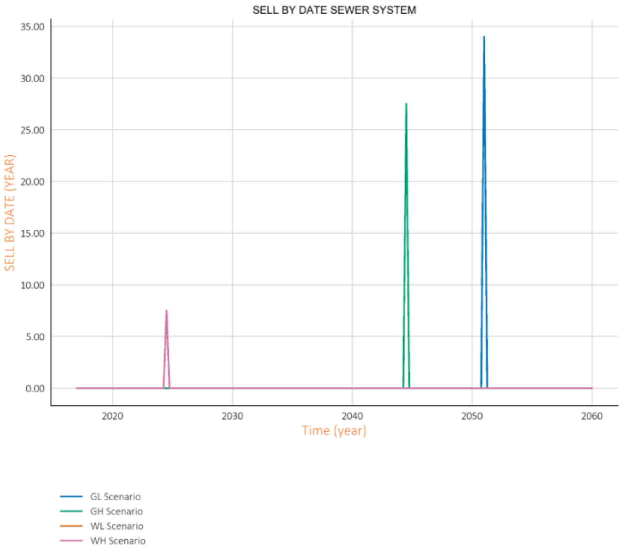

Figure 15. Sell by date of sewer system

REFLECTION ON CURRENT PRACTICES

The obtained results indicate that more insight was created in the dynamic uncertainty subjected to complex systems. This insight enriches the static approaches within infrastructure asset management that predominantly considers singe sector infrastructures. Furthermore, it provides the possibility to save costs, limit negative side effects and maximise the target effects due to maximal asset performance.

With the proposed approach intervention moments can be adapted to both the functional and technical lifetime of both the primary and secondary function (Figure 10 to 15). In current asset management practices interventions have to incorporate the technical and functional lifetime, for multiple functions at the same time. This involves the assessment of many variables and their underlying relations. Asset managers perceive it as challenging to incorporate all these variables and underlying relations with the available static decision support tools. Especially, when taking uncertain future developments into consideration, which affect the technical and functional lifetime for all functions. Therefore, interventions are not always based on both the technical and functional performance for all relevant functions (Rijkswaterstaat, 2015c; Appendix E.5, Interview Rijkswaterstaat). Rijkswaterstaat plans their replacements and renovations according to a designed technical life (Rijkswaterstaat, 2015c). However, the functional lifetime of the asset can be shorter than its technical lifetime. Furthermore, the secondary function of an asset can require an intervention sooner than the primary function. Interventions solely based on technical lifetime and single functions can thereby lead to double interventions, and a lack in performance.

Furthermore, the proposed approach provided insight in the occurrence and magnitude of future uncertain developments. The effect that the future developments had on both the functional and technical lifetime was predicted for both the primary and secondary function (Figure 10 to 15). In current asset management practices the occurrence and magnitude of uncertain developments are often hard to predict.
To cope with this uncertainty, asset managers often overestimate future developments, by applying large bandwidths or solely designing for the worst case (appendix E.2, Interview Antea Group; Appendix E.5, Interview Rijkswaterstaat; Appendix E.1, Interview Province of North Holland). It is perceived as challenging to gain insight in the many variables that are attached to these developments (Appendix E.5, Interview Rijkswaterstaat). However, overdesigning can be very costly and unnecessary.

When considering the future vision of the city of Amsterdam, it predicts to reach almost 1 million inhabitants in 2030 (Gemeente Amsterdam, 2016). Designing the road for 1 million inhabitants in 2030 would always entail a functional intervention (high urbanisation, Figure 12). If this vision turns out to be different, and a decline in population would occur, no functional intervention would be required at all (low urbanisation, Figure 12). It is therefore crucial to have sufficient insight in the occurrence and magnitude of these future developments. Furthermore, the port of Amsterdam predicts that it will distribute 300 MTPA in 2030 (Port of Amsterdam, 2015). However, this is strongly dependent on the economic growth scenario and the actual growth of the harbour due to available area. In a high economic growth scenario (Figure 10) functional lock interventions are required earlier than in low economic growth scenarios (Figure 10). Basing the intervention on the predefined expectation of the port of Amsterdam can lead to the unnecessary early implementation of these interventions.

4.3 DYNAMIC COMPLEXITY

In this section, the main results are presented regarding the dynamic complexity of infrastructure systems. First, the general results are described, after which examples from the case study are provided. Finally the results are reflected to the current practices in infrastructure asset management.

GENERAL RESULTS DYNAMIC COMPLEXITY

The second result observed from the simulations, was that insight was created in the complexity of the infrastructure asset systems. In other words, the influences that interconnected asset systems have on one another and other sub-models was observed.

INFLUENCE BETWEEN INFRASTRUCTURE AND SUB-MODELS

As expected, well-functioning infrastructure led to a better functioning city and harbour, and vice versa. Road congestions and insufficient lock capacities led to lower harbour distributions, and thereby lower local economic growth. High harbour distributions were only achieved when I/C factors of the infrastructure stayed low, in combination with high economic growth scenarios. Innovations as bigger locks and automated driving increased the amount of world offer to the harbour, due to scaling benefits and lower waiting times. Furthermore, well-functioning infrastructure led to larger city areas, bigger populations, more businesses, more jobs and larger local economies (appendix B). Underlying figures show the difference between the amount of MTPA distributed in the harbour, with and without interventions for the infrastructure asset systems.

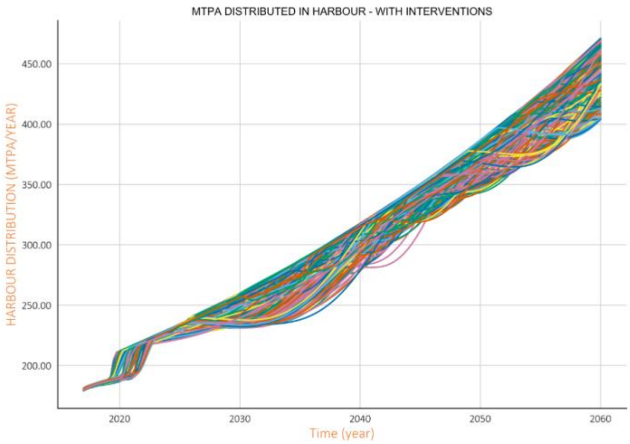

Figure 16. MTPA distributed in harbour with interventions

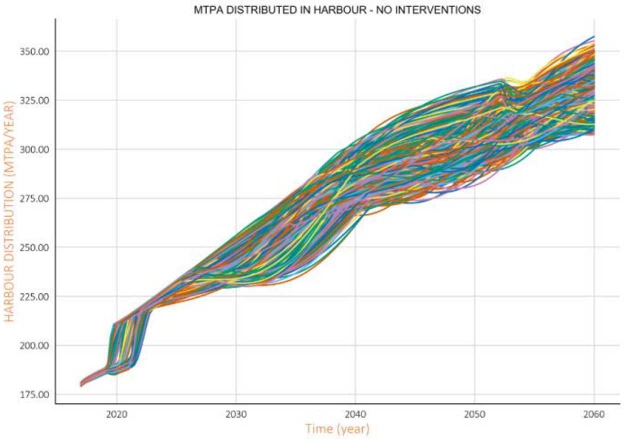

Figure 17. MTPA distributed in harbour without interventions

INFLUENCE BETWEEN INFRASTRUCTURE SYSTEMS

Another expected result, but less trivial to obtain, was the shifting of sell-by-dates of infrastructure asset systems, by interventions on interconnected infrastructure systems. Increasing, or decreasing the capacity of an asset system, can affect the tonnage distributed in the harbour. Moreover, well performing infrastructure systems attracted more businesses and larger population growth. These developments implicitly affected the traffic intensities for interconnected infrastructure systems, and thereby their sell-by-dates.

When comparing the sell-by-date of the same road policy, after building an innovative lock, or a non-innovative lock, the sell-by-date shifted towards an earlier date. The innovative lock, which is slightly wider than the non-innovative lock, increased the amount of larger vessels visiting the port (scaling benefits). Moreover, the innovative lock had slightly more capacity, causing less vessels to diverge to different harbours due to waiting times. This caused more truck flow, through which interventions on the road had to be performed earlier.

This interconnection was observed in the opposite direction as well. After applying a large renovation project for the road, a specific lock policy would not reach its sell-by-date. If instead of the renovation, additional lanes would be added to the whole road network, the lock system would reach its sell-by-date in an earlier stage. The road system was limiting the harbour distribution potential with the renovation policy, because insufficient extra capacity was created. Only after adding additional lanes, the vessel flow could reach its full potential.

This showed that interventions on one infrastructure system can be applied, but may be less effective if interconnected infrastructure systems are not planned accordingly.

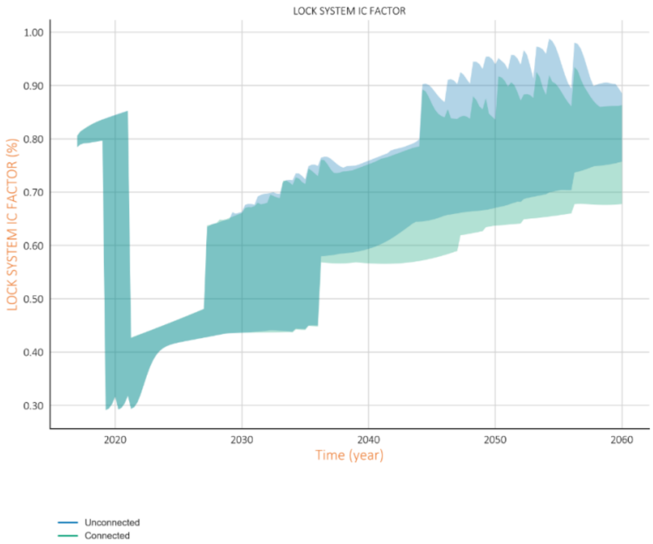

Figure 18.Lock I/C without road interventions

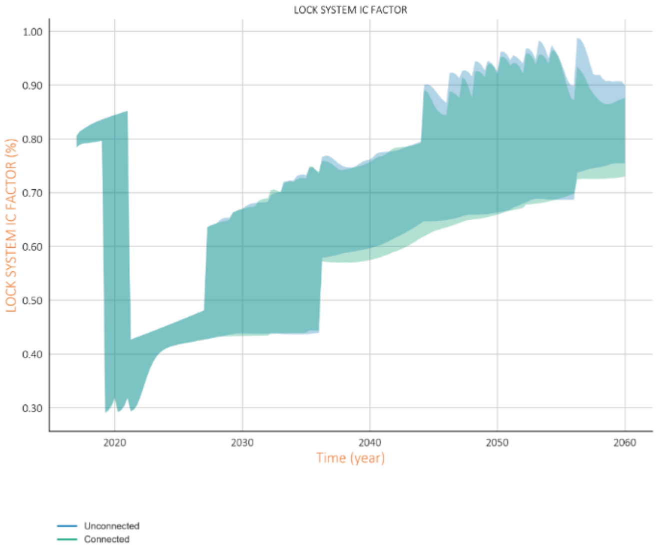

Figure 19. Lock I/C with road interventions

This influence of interventions is shown in the above figures. Simulations were performed, in which the influence of the infrastructure asset systems could be powered on, or off, with a switch. In an unconnected simulation the infrastructure asset systems receive the maximum amount of world offer, and thereby maximum traffic intensities (light blue colour). When the infrastructure asset systems are connected, they can limit one another (light green colour). When both the unconnected and connected simulations overlap, a dark green colour is presented. In Figure 18 it can be observed that the maximum intensity of vessel flow is limited in the connected simulation (lower I/C factors).

The road system, is limiting the harbour demand, and thereby vessel intensities through the lock. In Figure 19 an intervention was performed on the road system. It can be observed that the connected simulation showed more similar results to the unconnected simulation (less light green, more dark blue). In other words, the intervention on the road system increases the vessel flow through the lock. The same was observed in the opposite direction, when simulating the road I/C factor (appendix B).

REFLECTION ON CURRENT PRACTICES

The obtained results indicate that more insight was gained in the complexity resulting from the interconnection between the infrastructure asset systems and possible functions on multiple scales. This insight enriches the static approaches within infrastructure asset management that only consider singe sector infrastructures. It provides the possibility to save costs, limit negative side effects and maximise the target effects due to maximal asset performance.

With the proposed approach, interventions can be implemented on a network level, and the effects that these interventions have on other asset systems and sectors can be measured on an operational level (Figure 16 to 19 and appendix B). In current asset management practices it is perceived as challenging to translate the effects of an intervention from a network to operational level.
Therefore, decision-makers rarely develop a shared policy, in which all relevant stakeholders from different infrastructure systems are incorporated (Appendix E.2, Interview Antea Group; Appendix E.5, Interview Rijkswaterstaat). This can lead to the misinterpretation of the effects of an intervention, and thereby create insufficient performance of asset systems. Furthermore, only considering single sector asset systems can lead to the misinterpretation of influences on asset performance. The perceived asset performance can turn out to be different than expected. The unconnected (single sector) simulation showed different I/C factors than the connected (network) simulation (Figure 18, 19 and appendix B). A shared policy approach, that considers the entire network, can therefore provide more reliable information on the actual asset performance, and interventions can be implemented accordingly.

The next section will present how the proposed approaches can assist in the improvement of large intervention decisions, for a complex network of multifunctional infrastructure systems subjected to dynamic uncertainty.

4.4 IMPROVING LARGE INTERVENTION DECISIONS FOR AN INFRASTRUCTURE NETWORK

To improve the functioning of the infrastructure asset systems, policies were formed and implemented. The policies were implemented in three different uncertainty clusters: low, medium and hard (§2.3.3). For each cluster an adaptation pathways map was formed on a network level. This implied that a switch between policies had to be made, if one of the infrastructure systems reached a sell-by-date. The sell-by-dates were reached as a result of insufficient technical (T), functional (F) or multifunctional (M) performance. The latter meaning that the secondary function, flood protection (lock) or rainwater discharge (road), could be the first to reach its sell-by-date. Paragraph 4.4.2 will present and elaborate on the combined adaptation pathways map in which all uncertainty clusters are taken into account. A reflection to the current practices in infrastructure asset management will be provided An overview of all separate maps is presented in appendix D. Paragraph 4.4.1 will briefly elaborate on the intervention policies. Appendix C provides a more extensive overview of the intervention policies.

4.4.1 INTERVENTION POLICIES

This paragraph briefly presents the intervention policies that were used during this study. The intervention policies were seen as realistic options in literature and interviews. Two interventions at different moments in time are possible per infrastructure system. The possible interventions can differ per intervention moment. This study does not claim that these interventions are the most optimal, they were merely chosen since they have varying effects for the analysis on the used approach.

Lock 1st intervention

- Lock Noordersluis: a complete renovation of the Noordersluis, extending its lifetime beyond the simulation time;
- Lock No Inno: construction of a new lock, which is an exact copy of the new sea lock that is currently being constructed at IJmuiden (Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP).

Lock 2nd intervention

The second intervention is only applied in combination with the renovation of the Noordersluis. Building two completely new locks in a time period of 43 years, is unrealistic due to high costs.

- Lock No Inno: see lock 1st intervention;
- Lock Inno: construction of a new lock, which applies the latest innovations possible (Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP).

Road 1st intervention

- Road Inno: a complete renovation (variable maintenance intervention) of the Amsterdam Ring A10 (Rijkswaterstaat, 2017a), with additional innovative measures to extent the technical lifetime (Rijkswaterstaat, 2016a);
- Road Lanes: a complete renovation of the Amsterdam Ring A10 (large intervention) (Rijkswaterstaat, 2017a). In addition, 2 lanes (1 per direction) are added to the A10.

Road 2nd intervention

- Road Renovation: large renovation project on whole Amsterdam road network (A10 including parts of connecting roads A8, A5, A4, A6);
- Road Lanes 2: the adding of 2 lanes (1 per direction) to the whole Amsterdam road network (A10 including parts of connecting roads A8, A5, A4, A6).

Multifunctional intervention

The multifunctional interventions are not shown as policies in the pathways map. Their sell-by-dates are however taken into account. In other words, they can shift the sell-by-date of a policy combination to an earlier date (if not already adjusted during an earlier intervention). This is shown in tables 2,3 and 4 in appendix D.

- Heightening of door height, and/or retaining height of the remaining parts of the lock complex (Glerum & Vrijburcht, 2000; Rijkswaterstaat, 2009)
- Increasing sewer capacity by improving pump capacity, and installing larger pipe diameters.

4.4.2 COMBINED ADAPTATION PATHWAYS MAP

The combined adaptation pathways map presents the interventions required, for an optimal functioning of the infrastructure network in all simulation scenarios. The actual path dependencies are shown for the hard simulation, since this presents the most extreme conditions. The sell-by-dates for the policies in the low and medium simulation, are presented with an adjusted time scale. The combined map is presented in Figure 20.

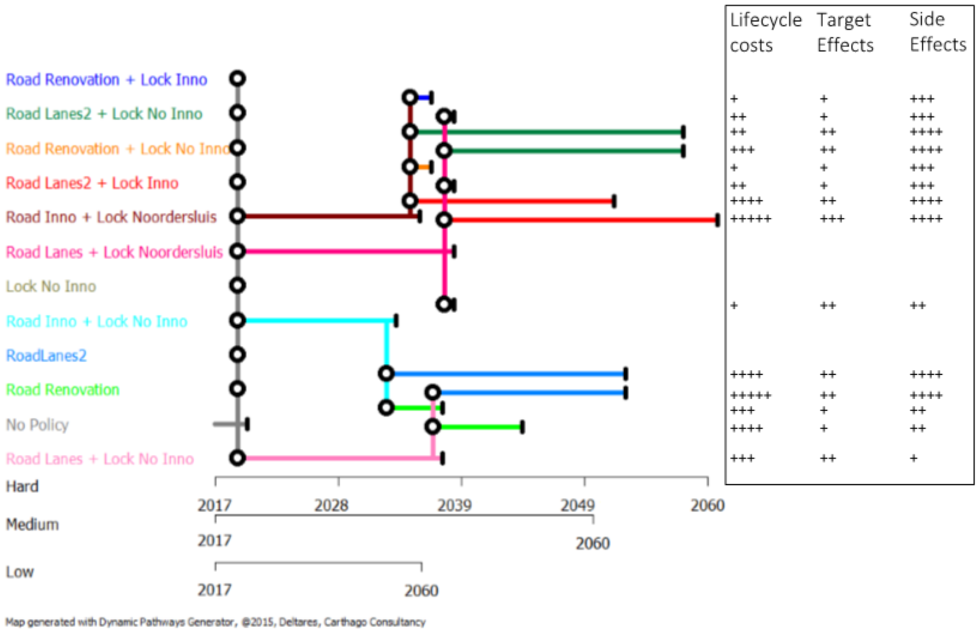

Figure 20. Combined adaptation pathways map of intervention policies including scorecard
On the left, the combination of intervention policies (appendix C) are listed. Each combination of intervention policies has certain lifecycle costs, target effects, and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The more '+' marks, the more lifecycle costs, the better the target effects (increasing asset performance), and the more negative side effects (hindrance, pollution etc.) are attached to the intervention policies. At the bottom, the time scale is presented for the hard, medium and low scenario. The figure is scaled on the hard scenario, the time scales for the medium and low scenario are adjusted to this scaling.

The first key finding was that interventions can be dynamically adapted over time, according to opportunities that where identified with the adaptation pathways map. In the hard simulation, the first sell-by-date for the road without interventions occurred in 2019 (T). Taking planning and construction time into consideration, an intervention needed to be initiated at the start of simulation. The sewer system would reach its sell-by-date in 2026. It would not be economically viable to break open the road for a sewer intervention after such a short time period. Moreover the sewer system is at the end of its technical lifetime within the design period of the intervention. Therefore the sewer system had to be replaced during the first road intervention.

The lock required at least two interventions in the hard simulation to not reach a sell-by-date. The planning of the second intervention needed to be initiated around 2030. Dependent on the applied road interventions, and the construction and planning time of the lock intervention. The embankments in between the locks reached insufficient retaining height in 2046. Therefore it was economically viable to adjust the retaining height after the second intervention was complete, and all machinery was still at the lock site (8 to 12 years after initiation).

In current asset management practices these opportunities are often overlooked, leading to unnecessary interventions, more costs, lower target effects and larger side effects. A survey amongst Dutch municipalities, water boards and provinces showed that 85% of the government bodies agree that climate change will have severe consequences for their infrastructure systems. However, only half of the government bodies takes climate change into consideration in their long-term planning (Arcadis, 2016). Overlooking opportunities in a long-term planning can lead to unnecessary interventions. If sewage capacities are insufficient, road structures will have to be opened before their technical/functional lifetime is expired. If flood protection structures have Insufficient retaining height, they will have to be adjusted during extra intervention moments. Furthermore, if interventions are initiated to late, flooding events can occur.

The second key finding was that strategic 'no regret' decisions can be identified for the first intervention moment, which can be dynamically adapted over time during the second intervention moment. A 'no regret' decision is an intervention which should be applied in all scenario packages, on the basis of costs, target effects and side effects. In real world situations, area for the required intervention can be reserved prematurely.

Momentarily a new sea lock is being constructed, which is expected to open in 2019 (if no delays occur). After the opening of the new sea lock, the I/C factor of the lock complex will rise above its threshold around the time that the Noordersluis has to close (T). Given all simulation scenarios, this will occur between 2027 and 2036. This sell-by-date can be avoided by either renovating the Noordersluis shortly after the new sea lock opens (when overcapacity is present), or by building an additional non-innovative lock. The initiation of the non-innovative lock has to start 8 years before the first possible sell-by-date is reached, when taking possible delays into account (planning and construction time). Since an investment of 850 million euros was just made for the new sea lock, it seems implausible to build an additional non-innovative lock at the first intervention moment. It seems more viable to renovate the Noordersluis, which yields lower costs and has shorter delay times. However, the renovation of the Noordersluis does require an additional new lock in a later stage, for all simulation scenarios. The non-innovative lock would not need a second intervention in the low and medium simulations. On the basis of net present value, it was clear that the renovation of the Noordersluis was the most viable solution during the first intervention moment, for all scenarios. The renovation of the Noordersluis and the additional lock that has to be built in a later stage, can yield a lower NPV than an early investment in a non-innovative lock. The specific lock that has to be built during the second intervention moment, can be chosen according to the future scenario that unfolds (Rijkswaterstaat, 2012b).

The road system reaches its first sell-by-date in an early stage for all simulation scenarios due to the end of technical life of the Ring A10 (T) (2019-2023). In real life this means that the first intervention decision has to be resistant against all future uncertainties, without any data on what uncertainties will probably unfold. During the first intervention the road innovation policy, or the adding of additional lanes could be applied. If the road innovation policy was to be implemented, an additional intervention would always be needed (for every simulation scenario). If instead, the road lanes policy was to be implemented, no additional interventions were required in the low scenario. On the basis of net present value, the low scenario showed that the road lanes policy was more economically viable, than applying a road renovation with any combination of policies during the second intervention. In the medium scenario package, both the innovation policy, as the road lanes policy, required an additional adding of road lanes during the second intervention. Given that the road innovation policy yields lower investment costs than the road lanes policy, the road lanes policy would be less economically viable in the medium scenario. If the road lanes policy would have extended the second intervention for additional road lanes far beyond the second intervention when applying the innovation policy, lower net present values could have been achieved. This was however not the case. Furthermore, in the hard simulation the innovation policy always reached a sell by date. The only viable option was the adding of road lanes during both interventions moments. Given the fact that the first intervention has to be implemented very early, in a stage were little is known about what future will probably unfold, it was found less risky to implement the road lanes intervention.

In current asset management practices interventions are predominantly overdesigned for the worst case scenario (Appendix E.2, Interview Antea Group; Appendix E.5, Interview Rijkswaterstaat). This can be unnecessary and very costly (Appendix E.1, Interview Province of North Holland). When considering the example of Myanmar (see 1.1 Problem Statement), which overdesigned its new capital city Naypyidaw, strategic 'no regret' decisions would have been more economically viable. Interventions with a smaller magnitude could have been implemented and adjusted as the future unfolded.

By gaining insight in which additional interventions might be necessary, area could have been reserved, and investments could have been postponed (Bruce, 2013; Kennard & Provost, 2015). Furthermore, this study does not claim that asset owners in the real world would have applied a different first intervention for the lock and road system. However, the used approach in this study provides a more substantial and informed basis for the interventions required. In current asset management practices it is perceived as challenging to gain insight in the effect an intervention has, whilst taking future uncertain developments into consideration. By applying the proposed method, the first interventions can be implemented with a high certainty degree for all possible future scenarios. Depending on the future that unfolds a strategic combination can be made with the second intervention.

The third key finding was that interventions can be adapted dynamically over time, by gaining insight in the required initiation of an intervention. Interventions can vary in their required planning and construction time. Most interventions usually go over this originally planned delay time, and interventions are thus often finished too late. By building in safety margins during the simulations, the first date at which policy makers would have to initiate an intervention was identified. Instead of starting plans after a problem is noticeable in the real world, policy makers can anticipate problems beforehand.

The road policy that might require the longest delay time is the adding of 2 road lanes (1 in both direction) to the whole Amsterdam road network. History has shown that interventions of this magnitude often took long planning, and construction times. Since this intervention is required in the medium, and hard simulation, policy makers can obtain the required sell-by-dates from the adaptation pathway maps, and start planning with an extensive safety margin in advance.

The lock policy that might require the longest delay time is the construction of a new innovative lock. History has shown that large lock interventions can take as long as large road interventions. An example can be taken from the new sea lock, which is currently constructed at IJmuiden. This lock will be the biggest lock in the world, and can momentarily be seen as an innovative lock. The study for this lock was initiated in 2002, and construction is expected to be finished in 2019. The construction of an additional new innovative lock will require less time, since an extensive study of the surrounding area has already been conducted. Furthermore, additional time for the research and implementation of innovations might be necessary. If this intervention is necessary, as is the case in the hard simulation, policy makers can obtain the required sell-by-date from the adaptation pathways map, and start planning with an extensive safety margin in advance.

In current asset management practices interventions are often initiated too late, and thereby affect the performance of infrastructure systems and other systems. The lock complex at IJmuiden reached its threshold (I/C > 0,6) in 2006, whilst the new sea lock of IJmuiden will be opened in 2019 (Rijkswaterstaat, 2012b). The large waiting times, and possibility to provide safe passage for larger vessels thereby limit the growth of the port of Amsterdam (Gemeente Amsterdam, 2011; Port of Amsterdam, 2015). By identifying the required initiation moment for interventions at an early stage, and taking possible delays into consideration, the new sea lock at IJmuiden could have been initiated in time.

The fourth key finding was that interventions can be adapted dynamically over time, by the identification of lock-ins and path dependencies. When considering the hard simulation every combination of policies would result in a lock-in, except for the most extensive combination (pink combined with red line). Lock-ins are points at which the sell-by date of an intervention policy is reached. In the medium simulation four different paths reached until the end. Each of these four paths was dependent on the 'Road Lanes 2' intervention. In the low simulation a wide variety of paths was sufficient for the simulation uncertainties. The renovation of the Noordersluis and the road innovation were however, always dependent on a second intervention. These lock-ins and path dependencies were useful when forming the most robust set of interventions, as is explained in the fifth key finding. The reflection on current practices within asset management is therefore presented in the fifth key finding as well.

The fifth key finding was that a most robust set of interventions can be found for each simulation scenario. As explained in the second key finding, 'no regret' actions were formed for the first intervention moment. The lock authority is advised to renovate the Noordersluis during the time that overcapacity is created by the new sea lock of IJmuiden. The road authority is advised to initiate the construction of additional road lanes at the beginning of the simulation period. The second intervention is dependent on the future scenario that will unfold.

In the low simulation only a non-innovative lock is advised during the second intervention moment. This yields the maximum amount of target effects, has the lowest lifecycle costs, and has the second lowest side effects.
In the medium simulation additional road lanes in combination with a non-innovative lock are advised. For the road this is the only policy combination without a sell-by-date. Furthermore, the non-innovative lock yields lower lifecycle costs, than the innovative lock. The proposed option yields the maximum amount of target effects and the largest negative side effects. The latter can't be avoided since two interventions are necessary. It could be argued that the more expensive innovation lock could increase the harbour distribution, and thereby the local economy due to scaling benefits. However, in the low and medium simulation the innovations are not very extensive, and major differences in the local economy were not observed. A contributor to this observation is that the lock currently constructed at IJmuiden is already the biggest lock in the world (wider than Panama).

In the hard simulation additional lanes in combination with an innovation lock are advised. This is the only policy combination without a sell-by-date. This policy yields maximum target effects, but also has large negative side effects, and is very expensive. The innovation lock is recommended since innovations could be more extensive, and thereby minimize the time needed for lock cycles. This would increase the lock capacity, which will be needed in extreme developments. In the hard simulation it is expected that automated driving and ITS will increase the roads capacity. However, since more people will start using their cars it will still be necessary to add additional lanes during both intervention moments. The intervention moment for the secondary function can be chosen strategically during the first, or second intervention moments. Since the first road intervention will add additional lanes in all future scenarios it is advised to adjust the sewer system during the first intervention moment. This results from the fact that the new road lanes will be designed for a lifetime of 100 years. The adjustment of the lock retaining height is only required in the hard simulation. Since this required intervention moment is shortly after the second required intervention moment, it is advised to adjust the retaining height after the second intervention is finished. This can be more economically viable. It is however recommended to perform a more extensive net present value calculation on this matter.

In current asset management practices decision-makers develop a static most optimal plan using a single most likely future. Thereby, they assume that the future can be predicted. However, if the future turns out to be different than planned, the plan has to be adjusted. These adjustments are often initiated too late, after problems already have occurred. This can induce larger costs, larger side effects, and lower target effects (Haasnoot et al., 2013).

These negative effects can be avoided by constructing an adaptive plan, with interventions to be taken in the short-term, and the establishment of a framework to guide actions in the future. The plan can thereby be adapted to new experiences and insights. Analysing beforehand how possible interventions might fail in future scenarios, enables the possibility to design future actions to guard against these failures. These future actions can be initiated in time, to ensure that the plan stays on track and reaches its objectives. By implementing a monitoring system, the exact initiation for the future actions can be updated throughout time (Haasnoot et al., 2013). The monitoring system can be performed by extending the adaptation pathways approach with the DAPP method (section 2.2.1). This is also recommended in this thesis (section 5.2.1).

4.5 REFLECTION ON HYPOTHESIS

Finally, building on all these findings, the combination of the ESDMA and adaptation pathways approach can improve the long-term planning of large intervention decisions within infrastructure asset management.

First, the dynamic complexity and uncertainty was assessed with the proposed approaches. Insight was created in the complex nature of infrastructure asset systems. This complexity resulted from the influence of interconnected infrastructure systems and their required multifunctional performance. Furthermore, for this network of multifunctional infrastructure systems, insight was created in the dynamic uncertain developments subjected to these systems. These uncertainties mainly resulted from developments in population, economy, innovation, climate, and land use. The technical and functional performance of the infrastructure systems were obtained at any given point in time, under every possible future scenario.

Second, by gaining insight in the dynamic complexity and uncertainty a more dynamic approach was obtained. This dynamic approach can enrich the static approach predominantly used within infrastructure asset management. Instead of overdesigning infrastructures for the worst case scenario, no regret decisions can be implemented and adjusted as the future unfolds. Required interventions can be identified and initiated in time to avoid possible problems. Policy combinations which result in a lock-in can be identified and avoided.
Furthermore, instead of only considering single sector infrastructures, this approach enables the consideration of an interconnected network of multifunctional infrastructure systems. Opportunities related to the implementation of interventions on multiple functions can be identified, which can ensure economic viability and timely implementation. The effect that interconnected infrastructure systems have on one another can be identified and taken into consideration during decision-making. Path dependencies can be identified to create insight in the required combination of interventions on an infrastructure network level. All these findings resulted in a most robust set of interventions for every possible future scenario, based on costs, side effects and target effects.

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The objective of this study was to analyse the contributions of a multivariate simulation method within the long-term planning of large intervention decisions in infrastructure asset management. This was performed by applying the combination of the ESDMA and adaptation pathways approach to the long-term planning of a network of complex multifunctional infrastructure asset systems, subjected to dynamic uncertainty. Specifically, within the long-term planning, large interventions had to be initiated to ensure the technical and functional performance of a multifunctional lock and road system. The lock system schematically represented the lock complex of IJmuiden, the road system represented the road network around Amsterdam. These systems were connected through the city of Amsterdam with its harbour, local economy, rail system, canal system, and a limited amount of area.

An adaptive long-term planning was formed for the lock and road system given any plausible future scenario. This long-term planning included a set of robust interventions for the primary (transportation) and the secondary (flood protection, sewer drainage) function.

Within the set of interventions for the lock system, the Noordersluis has to be renovated during the time that overcapacity is created by the new sea lock of IJmuiden. This new sea lock is expected to open in 2019. Depending on climate change and innovation scenarios the Noordersluis will reach its end technical lifetime between 2027-2036. If the renovation is initiated after this technical lifetime is reached, the renovation will cause I/C factors above the allowed threshold (0,6). This occurs in most future scenarios. In a later stage an additional new sea lock will have to be constructed according to the future that unfolds. In a high macro-economic growth scenario an additional ‘innovative lock’ is required. With high economic growth, traffic intensities are high, and innovations have to be extensive. These innovations can reduce the time needed for lock cycles, and increase the locks capacity. This capacity is needed for the high traffic intensities. In low and medium macro-economic growth scenario’s a replication of the new sea lock at IJmuiden will suffice.

The adjustment of the lock retaining height is only required in high climate change scenarios. Since this required intervention moment is shortly after the additional lock is constructed, it is advised to adjust the retaining height after construction of this lock is completed. All machinery and equipment will still be at the construction site, which leads to a higher economic viability.

Within the set of interventions for the road system, the construction of additional lanes for the Ring A10 needs to be initiated right away (during the current renovation project). In real life this means that this first intervention has to be resistant to all future uncertainties, without any data on what uncertainties will probably unfold. The early adding of road lanes, is the only robust (first) intervention that can suffice in scenarios with high urbanisation and macro-economic growth. In this high scenario, additional road lanes have to be constructed at a later stage. This is also the case for medium urbanisation and macro-economic growth scenarios. In low urbanisation and macro-economic growth scenarios, no additional interventions are required. Innovations as automatic driving and ITS showed to be of great importance to ensure sufficient road capacity in hard scenarios.

The underlying sewer requires an intervention dependent on the impacts of climate change. The road lanes that are constructed during the first intervention moment have a design horizon of 100 years. Since the intervention for the sewer system falls within this time horizon for all climate scenarios, it is advised to adjust the sewer capacity during the construction of the first additional road lanes. This avoids unnecessary interventions.

Developing these long-term plans for large intervention decisions, involved the assessment of dynamic complexity and uncertainty. Complexity resulting from the nature of infrastructure systems. They can influence one another due to their interfaces, and can perform multiple functions on different scales.
Uncertainty resulting from the environment an infrastructure system is situated in. This environment can be affected by developments in climate, economy, population, innovation, and land-use.

Within current asset management practices, these long-term plans are predominantly based on decision-support methods, which provide insufficient insight in the dynamic complexity and uncertainty subjected to infrastructure systems. These methods attain static input information, and are limited to the consideration of single sector infrastructure systems. As a result, policy makers within the field of infrastructure asset management, perceive it as challenging to implement the right decision at the right time, with so many variables, functions and uncertainties involved.

This study showed that the combination of the ESDMA and adaptation pathways approach can assess the dynamic uncertainty when subjected to a network of complex multifunctional infrastructure asset systems. The proposed approach can thereby contribute to the long-term planning of large intervention decisions. These contributions will be explained in three steps.

First, the complex nature of infrastructure systems was assessed. The first assessed aspect of complexity was the influence between interconnected infrastructure systems due to their local proximity, or dependencies on one another. It was found that decision-makers within infrastructure asset management rarely develop a shared policy in which all relevant stakeholders from different infrastructure systems are incorporated. It is perceived as challenging to translate the effects of an intervention from a network to operational level, with so many variables and underlying relations involved. This leads to the misinterpretation of the effects of an intervention, and thereby creates insufficient performance of asset systems.

The proposed approach assessed the interconnection between infrastructure asset systems. Interventions were implemented on a network level, and the effects that these interventions had on other asset systems and sectors were measured on an operational level. It was observed that an intervention on the lock system, increased or decreased the amount of tonnage distributed in the harbour. This change in harbour distribution affected the traffic intensity on the interconnected road system. The required magnitude and/or timing of an intervention for the road system shifted. This influence was observed in the opposite direction as well (from road to lock). Insight was created in the influence between infrastructure systems with direct interfaces, and infrastructure systems that indirectly influenced one another through other systems. The effects of an intervention could be interpreted dynamically over time, and subsequent interventions were implemented accordingly to assure maximum asset performance.

The second assessed aspect of complexity, was the multifunctional performance of the infrastructure systems. In current asset management practices interventions have to incorporate the technical and functional lifetime, for multiple functions at the same time. This involves the assessment of many variables and their underlying relations. Asset managers perceive it as challenging to incorporate all these variables and underlying relations with the available static decision support tools. Especially, when taking uncertain future developments into consideration, which affect the technical and functional lifetime for all functions. Therefore, interventions are not always based on both the technical and functional performance for all relevant functions. However, the functional lifetime of the asset can be shorter than its technical lifetime (or vice versa). Furthermore, the secondary function of an asset can require an intervention sooner than the primary function. This can lead to unnecessary interventions, which induce more costs, create negative side effects, and can influence the infrastructures performance.

With the proposed approach, the technical and functional performance of the lock and road system was predicted, under every possible future scenario. This was done for both the primary (transportation) and the secondary (flood protection, sewer drainage) function. Interventions for both functions were combined during the same intervention moment, to increase the economic viability of the long-term planning. An intervention for the lock retaining height was combined with the construction of a second new sea lock. Furthermore, the sewage capacity was enlarged during the construction of the first additional road lanes.

In real world practices there is a fair chance that these interventions would not have been combined. In the Netherlands, 85% of the government bodies agree that climate change will have severe consequences, but only half of the government bodies takes climate change into consideration. The interventions for the lock retaining height and the sewage capacity were mainly dependent on developments in climate change.
If climate change would not have been taken into consideration, the opportunity to combine the interventions would have been neglected. An extra intervention would be required in later stage to adjust the lock retaining height. Moreover, the road would have to be opened (before its end technical lifetime) to adjust the sewage capacity.

Second, the dynamic uncertainty subjected to the complex infrastructure systems was assessed. Currently, asset managers perceive it as challenging to gain insight in the magnitude and time of occurrence of future developments. To cope with this uncertainty, asset managers often overestimate future developments, by applying large bandwidths or solely designing for the worst case. Thereby, interventions are often overdesigned, which can lead to unnecessary costs.

The proposed approach assessed the dynamic uncertainty, subjected to the complex infrastructure systems. The technical and functional performance of the infrastructure systems in both their primary and secondary function was measured dynamically over time when subjected to dynamic uncertainty. With the use of key performance indicators the main influences on the primary transportation function of both the lock and the road were obtained. The functional performance was mainly affected by developments that directly influenced the traffic intensities (developments in macro-economy, city population, labour population, and innovation). Moreover, the functional performance was affected by the technical performance, which was mainly dependent on developments that influenced the deterioration and the technical lifetime of the infrastructure systems (developments in innovation and climate change). The technical and functional performance of the secondary function of both infrastructure systems was mainly dependent on developments in climate change. The higher the climate change scenario, the earlier interventions were required.

By gaining insight in the magnitude and time of occurrence of future developments, interventions were adjusted to the required performance of the road and lock system. Strategic ‘no regret’ decisions were identified to be taken in the short-term, and a framework was established to guide actions in the future. A ‘no regret’ decision is an intervention which has to be applied in all future scenarios, on the basis of costs, target effects and side effects. In the short-term the Noordersluis has to be renovated and additional road lanes have to be added to the A10. Depending on the future that unfolds, additional road lanes have to be constructed again, and either an ‘innovative’ or ‘non-innovative’ lock has to be built. To ensure maximum asset performance, the future developments with the highest impact on the performance of the infrastructure asset systems can be monitored in the real world. The framework can thereby be adapted to new experiences and insights.

Moreover, the interventions within this framework can require a long planning and construction time. If these interventions are initiated too late, this can affect the performance of infrastructure systems and other systems. An example can be taken from the lock complex at IJmuiden. A study was initiated in 1999 to analyse the possibilities for enlarging the locks capacity. From this study it was decided to build a new sea lock, which is supposed to be operative in 2019. However, in 2006 the lock complex reached its threshold for one of its key performance indicators (I/C >0,6). This induced larger waiting times for vessels, and limits the possibility to provide safe passage for larger vessels. The growth of the port of Amsterdam is thereby limited. In this study these insufficient performances were avoided, by building in safety margins for the delay times of large interventions. The framework provides an early identification for the required interventions.

Third, when reflecting to the transformation of cities into mega cities (see introduction), the proposed approach can contribute to the long-term planning of their infrastructure networks. If Amsterdam transforms into a mega city, the dynamic uncertainty and complexity subject to the long-term planning can be incorporated. With the proposed approach, the technical and functional performance of its infrastructure systems can be predicted under every possible future scenario. This can be done for both their primary and the secondary functions. The magnitude and timing of interventions can be identified, and adjusted to the required performance. The effects that interconnected infrastructure systems have on one another can be identified and taken into consideration in the long-term planning of large intervention decisions. Switches between strategies can be made according to the future developments that unfold, and opportunities that are identified. Costs, time and negative side effects can be minimized. The target effects (performance) of the infrastructure systems can be maximized to create maximum value. All this can be performed on a more substantial and informed basis.

5.2 RECOMMENDATIONS

This study has shown that the combined ESDMA and adaptation pathways approach has the potential to contribute to the long-term planning of large intervention decisions within infrastructure asset management. During this study general recommendations were formed on how the combined approach can be improved by applying addition research for future use (paragraph 5.2.1). Furthermore some general limitations of this study were formed, which have to be assessed in future research (paragraph 5.2.2).

5.2.1 RECOMMENDATIONS FOR FUTURE USE

- Improve visualization adaptation pathways

  Additional research is recommended to improve the visualisation of the results of the ESDMA approach, in the adaption pathways. The ESDMA approach is able to simulate every combination of scenarios in a wide range of uncertainties. When visualizing the output of the ESDMA analysis into adaptation pathways, the scenarios have to be formed into packages. This limits the results to a small number of plausible futures, and thereby excludes a wide variety of scenario combinations. Moreover, in the combined adaptation pathways map, only one scenario package can be presented, and the timescale for the other packages is adjusted. This does not adequately visualize the required timing of an action for the packages with adjusted timescales. A final point for the visualization of the adaptation pathways concerns the time of actions for a network of infrastructure asset systems. When constructing a map for a network of infrastructure systems, the map provides limited insight on what system requires an intervention, and at which time it has to be initiated.

- Practical use in real world

  Additional research is recommended to the practical use of the combined approach in infrastructure asset management. The combined approach has important contributions for infrastructure asset management. However, practical implementation needs to be assessed. Building a specific model imply large costs and time, whereas a too general model result in less satisfying outcomes. The model used in this study was made more specific for the case and although the model could be made more specific, building the model already took a lot of time. Furthermore, a certain degree of training and practice is required before the approach can be used in a satisfactory manner. A standardised method, with a set of standardised sub-models that can easily be made more case specific might assist in overcoming these challenges.

- Extend usage of combined approach to a dynamic adaptive policy plan (DAPP)

  When applying an asset management strategy, the results of the combined approach should be extended to a dynamic adaptive policy plan (DAPP). This enables the implementation and monitoring of the actions in real-world projects. Furthermore, by extending the approach with a DAPP, the approach increases its ability to be anticipatory and reactive against a deep uncertainty level.

- Geographical dependent sub-models

  The model built in this study is not constructed on geographical dependency. More specifically, the city, harbour, lock and road sub-model are not dependent on their specific location within the total area. In the real world, expansion of a road or lock is dependent on the exact location of the congestion problem in the network and the available area at that location. Moreover, the possible costs, target effects and side effects will be different per location. To improve the practical implementation of the model, it is recommended to make the model geographical dependent.

- Political climate

  The future uncertainties described in this study, do not include developments of the political climate. Nevertheless, the political climate is an important factor in decision-making. Decision-makers can decide on the importance of specific interventions and scenarios, by ranking their available budget according to their preferences. This effect is hard to model in an infrastructure asset oriented model, for which the effects of the scenarios are translated to specific (technical and functional) impacts for the asset systems.

However, political influences can shift a preferred intervention policy, found by the adaptation pathways, to another policy. When making real-world decisions, it is thereby recommended to reflect the preferred intervention policy, to the current political climate.

- Extreme events

  In this study, extreme events in future uncertainties were not simulated, because these fell outside the scope of this research. Examples of extreme events are an economic crises or hurricanes. The effects of these extreme events can be excessive, and could have a large effect on the functionality of the asset systems. It is therefore recommended to include some extreme event simulations, and to visualise the possible impacts of these events on the asset performance.

- Rail and Canal

  For simplicity, it was assumed that the rail and canal system of the case study had sufficient capacity until the considered time horizon. The assumption was made to allow the use of relatively fast and simple models, and because the focus of this study was on the lock and road system. However, the rail and canal system have (primary and secondary) interfaces with the lock and road system and are mutually dependent. Traffic intensities for the lock and road system could diverge to other systems due to changes in transport type of the users and/or cargo. The intensities for the rail and canal system can thereby increase. For a more detailed simulation for this specific case study, it is recommended to include separate SD sub-models for the rail and the canal system.

- Expand number of interviews

  This study used expert interviews to gain insight in the main challenges and limitations subject to the currently used decision-support methods within the long-term planning of infrastructure asset management. The main challenges and limitations were obtained from a limited amount of interviews. To improve the practical implementation of the combination of the approaches, it is recommended to perform additional interviews and thereby address a wider scope of challenges and limitations.

5.2.2 GENERAL LIMITATIONS REQUIRING ADDITIONAL RESEARCH

- Use of relatively simple models

  The model built in this study can be made more specific, and the scope of their impacts can be made more extensive. The model used in this study relies on some simplicity due to time constraints, limited available information, and the required use of relatively fast and simple models. Moreover, the main focus lied on providing insight in the method for infrastructure asset management and the associated dynamics. Policy makers in the real world might have a wider interest in specific behaviour and impacts.

- Use of one singular case

  The combined approach has to be applied to more and different infrastructure asset management cases. During this study the combined approaches were applied to one singular case. To prove the usability of the combined approaches within the field of infrastructure asset management, more and different infrastructure asset management cases have to be assessed.

- Use of estimated values, and simplified calculations

  The main scope of this study was on the contributions of the combined approach within the field of infrastructure asset management. The model used within this study required many input values within various different fields. The input was retrieved from literature to the extent that this was possible. For uncertain values a bandwidth was used to minimize the risks of wrong values. This study acknowledges that even though all sub-models were verified and validated, not all values and results are representative for the case study. Furthermore, simplified calculations had to be made due to time constraints, and the limited scope of this study. It is recommended that these calculations are performed more extensively (net present value, basin capacity, vessel flow capacity, sewer capacity, car traffic capacity, deterioration etc.)

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APPENDICES

APPENDIX A – MODEL VERIFICATION

Model verification is performed to test the model structure, and consequent behaviour. First, the smallest time step is chosen, in line with the Euler integration method. Second, the model is simulated up to the time horizon of 2100 in order to check whether the chosen time horizon is appropriately.

A.1 TIME STEP

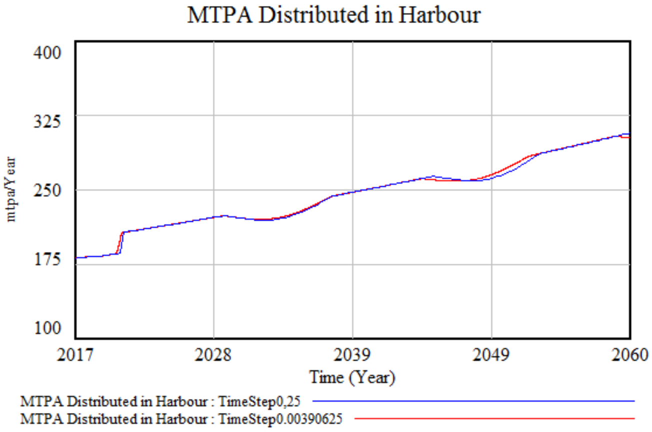

Figure 21. Large time step reflected to a small time step `

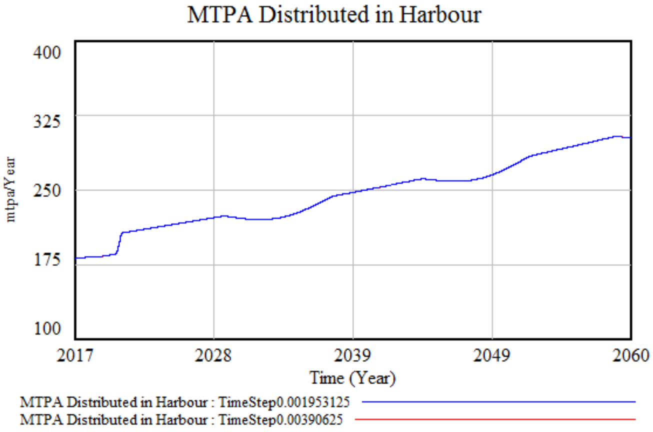

Figure 22. Last time step comparison, without differences

A.2 TIME HORIZON

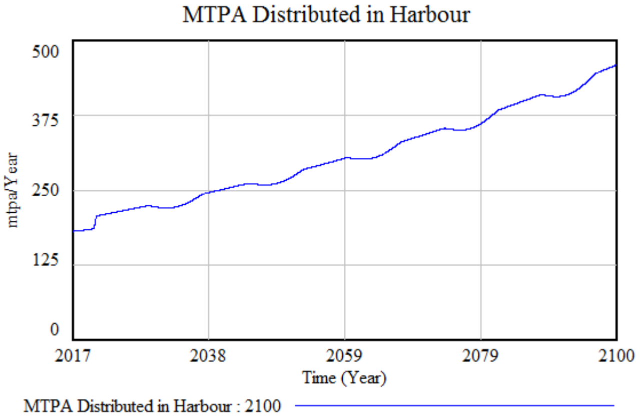

Figure 23. Harbour MTPA simulated in VENSIM up to 2100

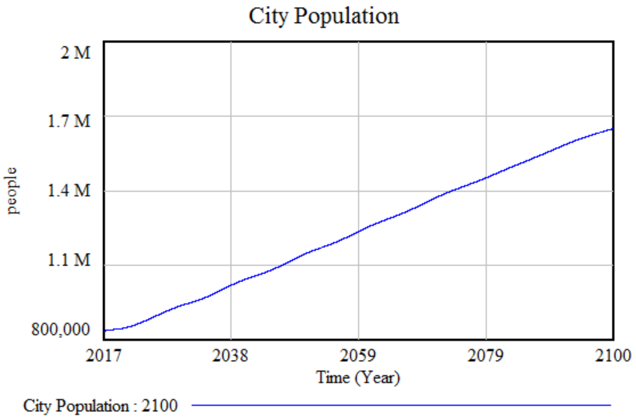

Figure 24. City Population simulated in VENSIM up to 2100

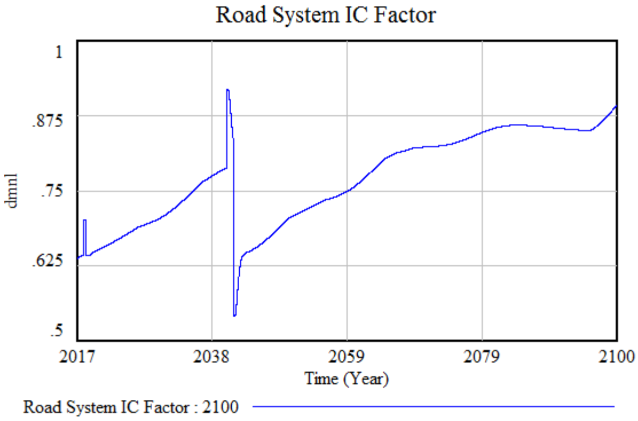

Figure 25. Road System IC simulated in VENSIM up to 2100

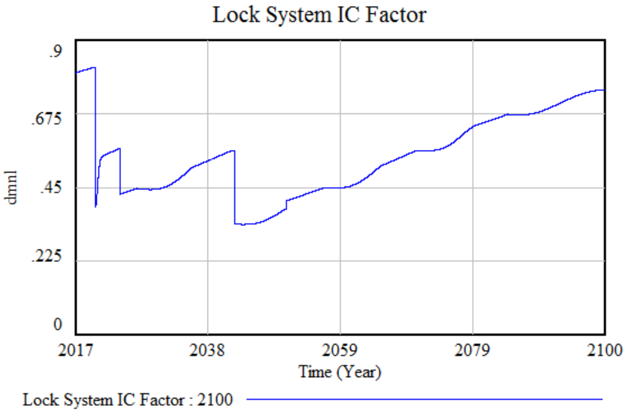

Figure 26. Lock System IC simulated in VENSIM up to 2100

APPENDIX B – EMA SIMULATIONS

This appendix is a short overview of the uncertain model variables including bandwidths and most important EMA simulation results. A repository with the source code and data can be found on GitHub (https://github.com/MHavelaar/ThesisIAM).

B.1 MODEL VARIABLES

Table 2. Overview of the uncertain model variables including the bandwidth.
The table includes the bandwidths supported with a source (if applicable). Underlying variables are used for the GENERAL simulations. For constructing pathways most variables were, dependent on the scenario package, considered as constants. Variables attached to the various scenarios were modelled using a 'switch' and are therefore excluded from this table. Most uncertainties are provided with a bandwidth of +/- 20%.

Variable	Unit	Min. Value	Max. Value	Source
Forecast Time Forecasting Policy	Year	1	4	Assumption
Normal Land use per house	ha/house	0.024	0.036	(OIS Amsterdam, 2016)
Planning Time Houses	Year	1	5	Assumption
Construction Time Houses	Year	1	3	Assumption
Delay Order House Construction	Dmnl	1	5	Assumption
Technical Lifetime Houses	Year	300	500	(OIS Amsterdam, 2016)
Normal Land Use per Business	ha/business	0.047	0.072	(OIS Amsterdam, 2016)
Number of jobs per harbour mtpa	Jobs/mpta/year	100	150	(Port of Amsterdam, 2015)
Planning Time Business	Year	1	5	Assumption
Construction Time Business	Year	1	3	Assumption
Delay Order Business Construction	Dmnl	1	5	Assumption
Technical Lifetime Business	Year	150	250	(OIS Amsterdam, 2016)
Planning Time Harbour	Year	1	5	Assumption
Construction Time Harbour	Year	1	3	Assumption
Delay Order Harbour Construction	Dmnl	1	5	Assumption
Technical Lifetime Harbour	Year	150	250	Assumption
Planning Time New Construction Road	Year	5	15	(Arts, 2007)
Planning Time Renovation Road	Year	1	3	Assumption
Renovation Time Road	Year	0.25	1	(Rijkswaterstaat, 2017a)
Construction Time Road	Year	1	5	(Rijkswaterstaat, 2017b)
Closure Rate Road A10 Intervention	Dmnl	0.33	0.50	Assumption
MTPA to Truck Factor	Mtpa/mvt	0.000004	0.000006	(RDW, 2012)
PCE to MVT factor	PCE/mvt	0.5	2	(Rijkswaterstaat, 2015a)
Delay Time Congestion Divergence	Year	0.5	1	Assumption
Delay time divergence factor	Year	0.5	1.5	Assumption
Delay time Scaling Benefits	Year	0.5	1.5	Assumption
Construction Time New Sea Lock	Year	2	4	(Rijkswaterstaat, 2016b; Appendix E.6, Interview BAM PPP)
Planning Time ReOpening old Noordersluis	Year	2	4	Assumption
Construction Time ReOpening old Noordersluis	Year	2	4	Assumption
Construction Time New Sea Lock No Innovation	Year	2	4	(Rijkswaterstaat, 2016b; Appendix E.6, Interview BAM PPP)
Planning Time New Sea Lock No Innovation	Year	2	4	(Rijkswaterstaat, 2016b; Appendix E.6, Interview BAM PPP)
Planning Time New Sea Lock Innovation	Year	3	6	Assumption
Construction Time New Sea Lock Innovation	Year	3	6	Assumption
Initial MTPA Leisure Vessels	Mtpa/year	2	4	Assumption

B.2 GENERAL – DYNAMIC UNCERTAINTIES

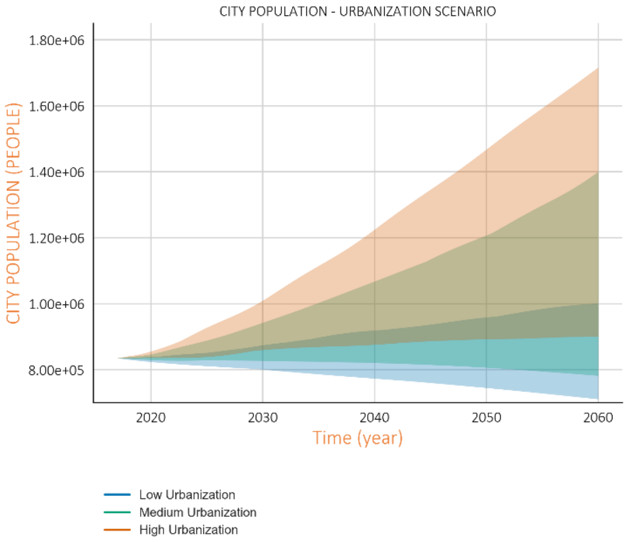

Figure 27. City Population – without asset interventions

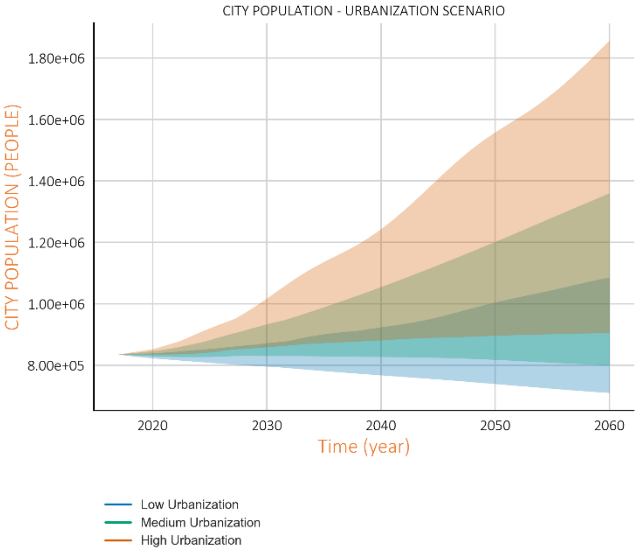

Figure 28. City Population – with asset interventions

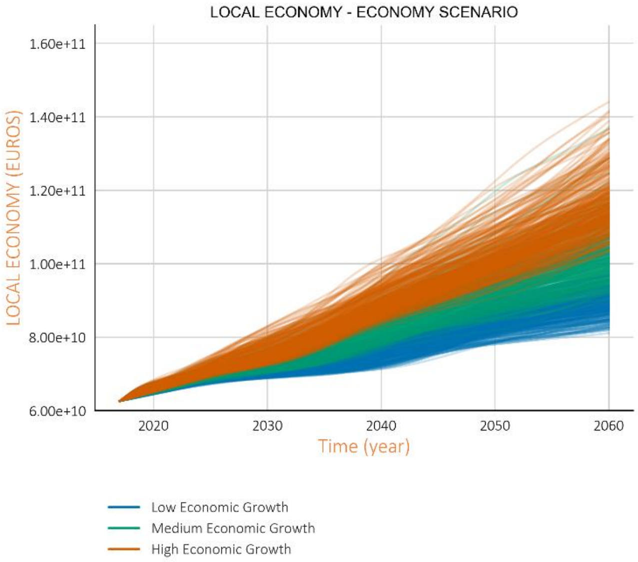

Figure 29. Local Economy – without asset interventions

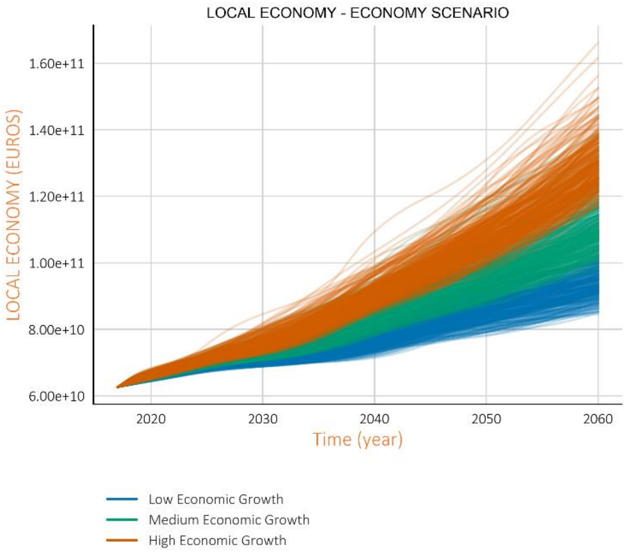

Figure 30. Local Economy – with asset interventions

B.3 ASSET CONNECTION - COMPLEXITY

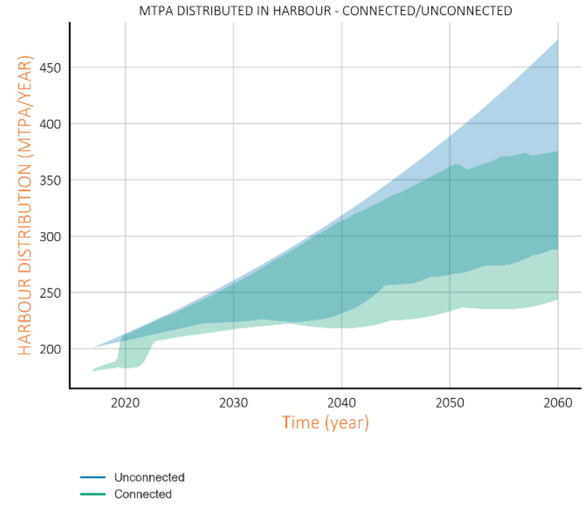

Figure 31. Harbour MTPA – without asset interventions

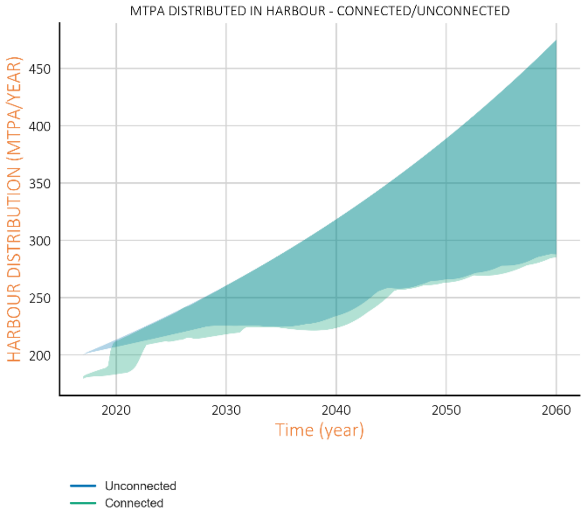

Figure 32. Harbour MTPA – with asset Interventions

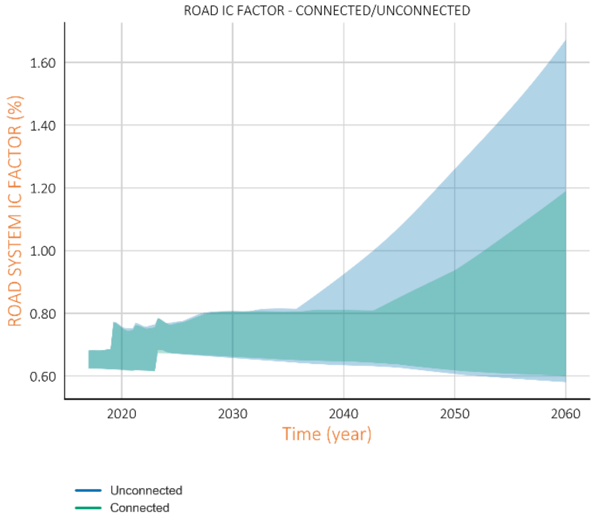

Figure 33. Road IC – without lock interventions

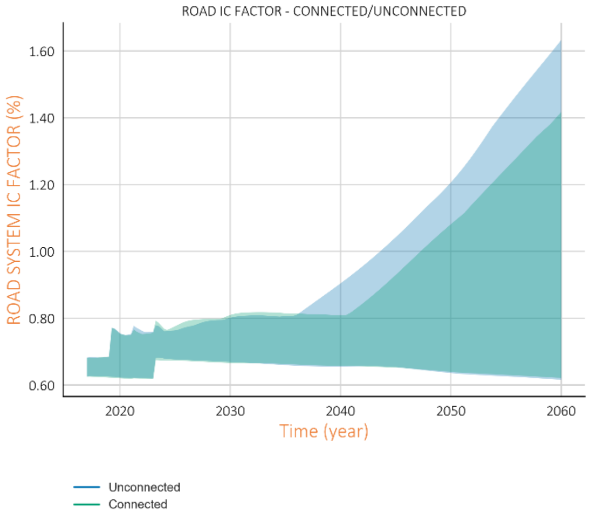

Figure 34. Road IC – with lock interventions

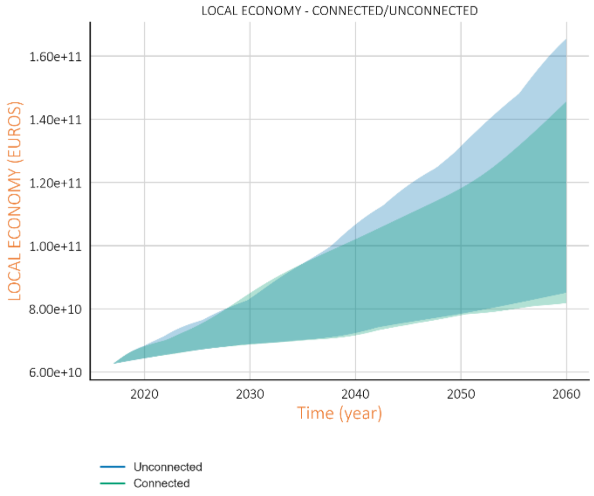

Figure 35. Local Economy – without asset interventions

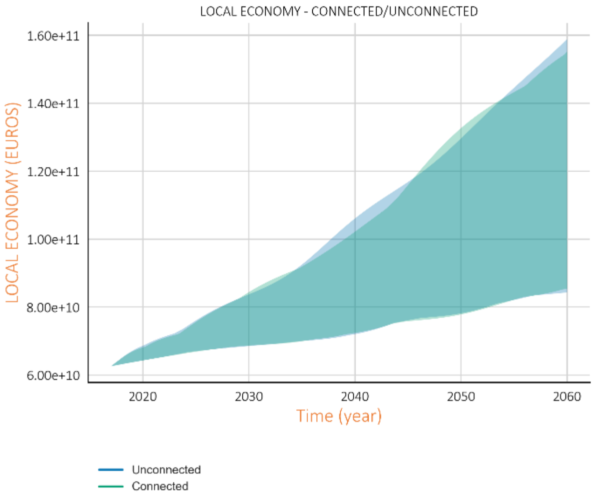

Figure 36. Local Economy – with asset interventions

APPENDIX C – INTERVENTION POLICIES

Lock 1st intervention

- Lock Noordersluis: a complete renovation of the Noordersluis, extending its lifetime beyond the simulation time. This intervention, in combination with building an extra lock in the future, can be a cheaper solution than building two entirely new locks, for larger harbour demands; Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP)
- Lock No Inno: construction of a new lock, which is an exact copy of the new sea lock that is currently being constructed. This lock does not apply the latest innovations possible. Scaling benefits, due the passage of the largest vessels can be less than when building an innovation lock. However, since this lock is already been built, construction, and planning times can be shorter. This can reduce costs. (Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP)

Lock 2nd intervention

The second intervention is only applied in combination with the renovation of the Noordersluis. Building two completely new locks in a time period of 43 years, is unrealistic.

- Lock No Inno: see lock 1st intervention;
- Lock Inno: construction of a new lock, which applies the latest innovations possible. Since this lock can be larger, scaling benefits can increase the world offer to the harbour for larger vessels. Moreover, since this lock can have a bigger capacity, due to its size, or faster completion of lock cycles, less waiting times can result in less vessels diverging to different harbours. This lock might induce longer planning, and construction times, since it has never been built, or tested before. Furthermore, this lock can be more expensive. This intervention is not applied during the 1ste intervention moment, since innovations may take some time to be profitable. (Rijkswaterstaat, 2012b; Appendix E.6, interview BAM PPP)

It has to be mentioned that in the low simulation, the renovation of the Noordersluis could also suffice with an additional renovation of the Middensluis. However, this policy was not used in the adaptation pathways map, since it required an additional new lock shortly after the renovation of the Middensluis.

Road 1st intervention

- Road Inno: a complete renovation (variable maintenance intervention) of the Amsterdam Ring A10 (Rijkswaterstaat, 2017a), with additional innovative measures to extent the technical lifetime. Innovative measures can extend the technical lifetime of asphalt layers, and thereby delay the intervention moment (Rijkswaterstaat, 2016a).
- Road Lanes: a complete renovation of the Amsterdam Ring A10 (large intervention) (Rijkswaterstaat, 2017a). In addition, 2 lanes (1 per direction) are added to the A10.

Road 2nd intervention

- Road Renovation: large renovation project on whole Amsterdam road network (A10 including parts of connecting roads A8, A5, A4, A6). Projects of this size will have large impacts on the environment, it will include large costs, and cause temporary congestions;
- Road Lanes 2: the adding of 2 lanes (1 per direction) to the whole Amsterdam road network (A10 including parts of connecting roads A8, A5, A4, A6). Projects of this size will have large impacts on the environment, it will include large costs, and cause temporary congestions. Often large road intervention projects took long planning, and construction times, and will cause a lot of objection from the local inhabitants due to its impacts.

It has to be noticed that the interventions are slightly different interventions than the intervention currently applied on the ring A10 (Rijkswaterstaat, 2017a). In the adaptation pathways map however, the intention is to reflect on the current policies, and visualise the impact of alternative policies with respect to the ‘do nothing’ alternative. The base case simulation therefore includes no intervention on the road ring A10.

Multifunctional intervention

The multifunctional interventions are not shown as policies in the pathways map. Their sell-by-dates are however taken into account. In other words, they can shift the sell-by-date of a policy combination to an earlier date (if not adjusted during an earlier intervention).

- Heightening of door height, and/or retaining height of the remaining parts of the lock complex. It can be more economically viable to adjust the retaining height of the lock complex, during interventions on the lock capacity. All equipment and materials are already present at the lock site. (Glerum & Vrijburcht, 2000; Rijkswaterstaat, 2009)
- Increasing sewer capacity by improving pump capacity, and installing larger pipe diameters. It can be more economically viable to adjust the sewer capacity during interventions on the road. Breaking open asphalt layers before their end of technical lifetime, can be costly.

APPENDIX D – ADAPTATION PATHWAYS

D.1 ADAPTATION PATHWAYS – LOW SCENARIO

Sell By Date Sewer: 2051
Sell By Date Lock Door remaining Parts height: -

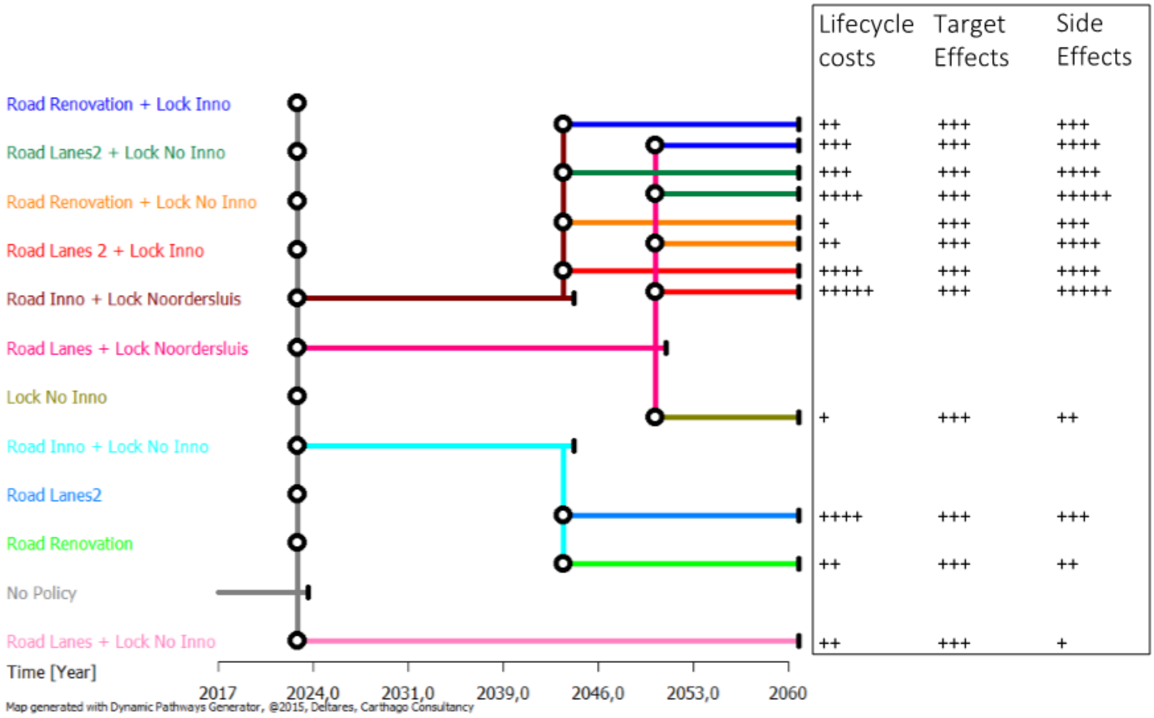

Figure 37. Adaptation pathways map of intervention policies for the low scenario, including scorecard
On the left, the combination of intervention policies (appendix C) are listed. Each combination of intervention policies has certain lifecycle costs, target effects, and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The more '+' marks, the more lifecycle costs, the better the target effects, and the more negative side effects are attached to the intervention policies. At the bottom, the time scale is withdrawn for the low scenario.

Table 3. Sell-by-dates adaptation pathways map – Low Scenario
On the left, the combination of intervention policies (appendix C) are presented. The sell-by-dates of the road and lock are presented, including the category (T = Technical, F = Functional). Furthermore, it is indicated whether the sewer or flooding height is intervened in the first or secondary intervention moment.

Policy 1 (*1st intervention*)	Policy 2 (*2nd intervention*)	Sell-By-Date Road (*+Category*)	Sewer Intervention (*1st / 2nd Int.*)	Sell-By-Date Lock (*+Category*)	Flooding Height intervention (*1st / 2nd Int.*)
Road Inno + Lock Noordersluis	Road Renovation + Lock Inno	-	2nd	-	-
Road Lanes + Lock Noordersluis	Road Renovation + Lock Inno	-	1st	-	-
Road Inno + Lock Noordersluis	Road Lanes2 + Lock No Inno	-	2nd	-	-
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock No Inno	-	1st	-	-
Road Inno + Lock Noordersluis	Road Renovation + Lock No Inno	-	2nd	-	-
Road Lanes + Lock Noordersluis	Road Renovation + Lock No Inno	-	1st	-	-
Road Inno + Lock Noordersluis	Road Lanes2 + Lock Inno	-	2nd	-	-
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock Inno	-	1st	-	-
Road Inno + Lock Noordersluis	-	2043 (T)	-	2050 (T)	-
Road Lanes + Lock Noordersluis	-	-	1st	2050 (T)	-
Road Inno + Lock No Inno	-	2043 (T)	-	-	-
Road Inno + Lock No Inno	Road Lanes2	-	2nd	-	-
Road Inno + Lock No Inno	Road Renovation	-	2nd	-	-
No Policy	-	2023 (T)	-	2031 (F)	-
Road Lanes + Lock No Inno	-	-	1st	-	-

D.2 ADAPTATION PATHWAYS – MEDIUM SCENARIO

Sell By Date Sewer: 2045
Sell By Date Lock Door remaining Parts height: -

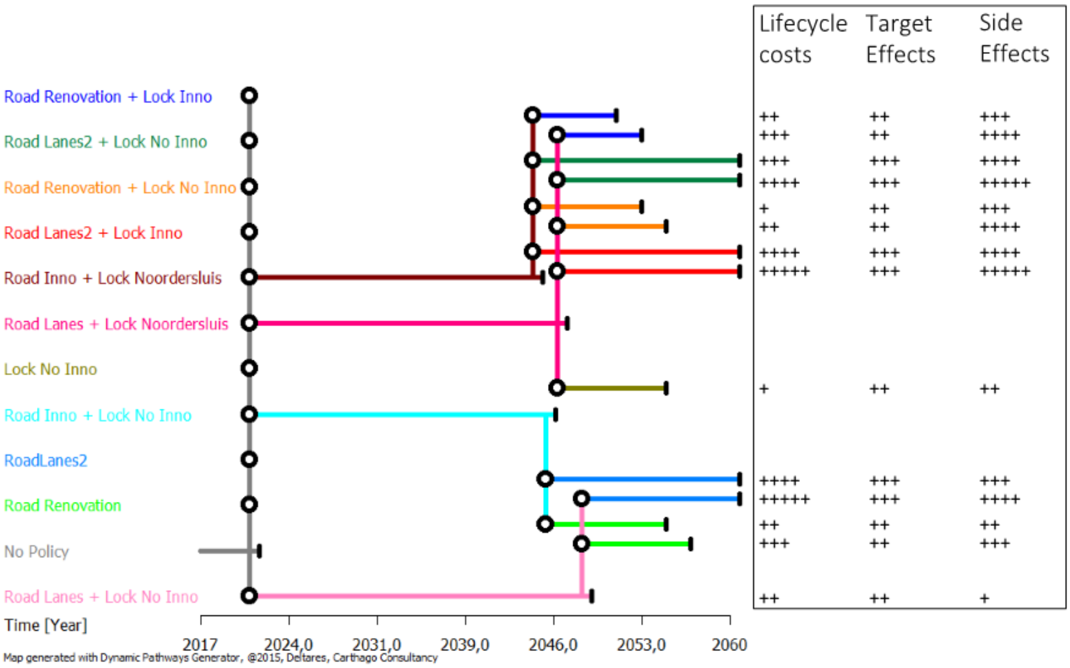

Figure 38. Adaptation pathways map of intervention policies for the medium scenario, including scorecard
On the left, the combination of intervention policies (appendix C) are listed. Each combination of intervention policies has certain lifecycle costs, target effects, and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The more '+' marks, the more lifecycle costs, the better the target effects, and the more negative side effects are attached to the intervention policies. At the bottom, the time scale is withdrawn for the medium scenario.

Table 4. Sell-by-dates adaptation pathways map –Medium Scenario
On the left, the combination of intervention policies (appendix C) are presented. The sell-by-dates of the road and lock are presented, including the category (T = Technical, F = Functional). Furthermore, it is indicated whether the sewer or flooding height is intervened in the first or secondary intervention moment.

Policy 1 (1st *intervention)*	Policy 2 *(2nd intervention)*	Sell-By-Date Road *(+Category)*	Sewer Intervention *(1st / 2nd Int.)*	Sell-By-Date Lock *(+Category)*	Flooding Height intervention *(1st / 2nd Int.)*
Road Inno + Lock Noordersluis	Road Renovation + Lock Inno	2050 (F)	1st	-	-
Road Lanes + Lock Noordersluis	Road Renovation + Lock Inno	2052 (F)	1st	-	-
Road Inno + Lock Noordersluis	Road Lanes2 + Lock No Inno	-	1st	-	-
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock No Inno	-	1st	-	-
Road Inno + Lock Noordersluis	Road Renovation + Lock No Inno	2052 (F)	1st	-	-
Road Lanes + Lock Noordersluis	Road Renovation + Lock No Inno	2054 (F)	1st	-	-
Road Inno + Lock Noordersluis	Road Lanes2 + Lock Inno	-	1st	-	-
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock Inno	-	1st	-	-
Road Inno + Lock Noordersluis	-	2051 (T)	1st	2044 (F)	-
Road Lanes + Lock Noordersluis	-	2054 (F)	1st	2046 (F)	-
Road Inno + Lock No Inno	-	2045 (F)	1st	-	-
Road Inno + Lock No Inno	Road Lanes2	-	1st	-	-
Road Lanes + Lock No Inno	Road Lanes2	-	1st	-	-
Road Inno + Lock No Inno	Road Renovation	2054 (F)	1st	-	-
Road Lanes + Lock No Inno	Road Renovation	2056 (F)	1st	-	-
No Policy	-	2021 (T)	-	2032 (T)	-
Road Lanes + Lock No Inno	-	2048 (F)	1st	-	-

D.3 ADAPTATION PATHWAYS – HARD SCENARIO

Sell By Date Sewer: 2024

Sell By Date Lock Door remaining Parts height: 2046

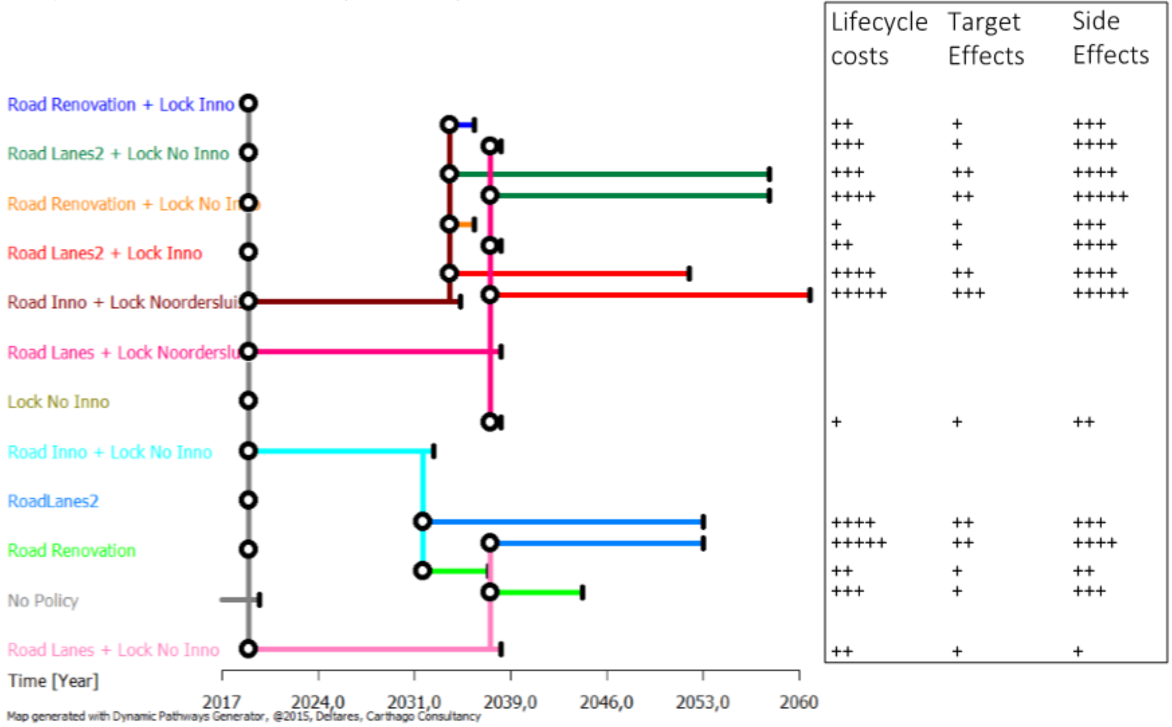

Figure 39. Adaptation pathways map of intervention policies for the hard scenario, including scorecard
On the left, the combination of intervention policies (appendix C) are listed. Each combination of intervention policies has certain lifecycle costs, target effects, and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The more '+' marks, the more lifecycle costs, the better the target effects, and the more negative side effects are attached to the intervention policies. At the bottom, the time scale is withdrawn for the hard scenario.

Table 5. Sell-by-dates adaptation pathways map – Hard Scenario
On the left, the combination of intervention policies (appendix C) are presented. The sell-by-dates of the road and lock are presented, including the category (T = Technical, F = Functional). Furthermore, it is indicated whether the sewer or flooding height is intervened in the first or secondary intervention moment.

Policy 1 (*1st intervention)*	Policy 2 *(2nd intervention)*	Sell-By-Date Road *(+Category)*	Sewer Intervention *(1st / 2nd Int.)*	Sell-By-Date Lock *(+Category)*	Flooding Height intervention *(1st / 2nd Int.)*
Road Inno + Lock Noordersluis	Road Renovation + Lock Inno	2034 (F)	1st	-	2nd
Road Lanes + Lock Noordersluis	Road Renovation + Lock Inno	2037 (F)	1st	-	2nd
Road Inno + Lock Noordersluis	Road Lanes2 + Lock No Inno	2058 (F)	1st	-	2nd
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock No Inno	2058 (F)	1st	-	2nd
Road Inno + Lock Noordersluis	Road Renovation + Lock No Inno	2034 (F)	1st	-	2nd
Road Lanes + Lock Noordersluis	Road Renovation + Lock No Inno	2037 (F)	1st	-	2nd
Road Inno + Lock Noordersluis	Road Lanes2 + Lock Inno	2051 (F)	1st	-	2nd
Road Lanes + Lock Noordersluis	Road Lanes2 + Lock Inno	-	1st	-	2nd
Road Inno + Lock Noordersluis	-	2032 (F)	1st	2037 (F)	-
Road Lanes + Lock Noordersluis	-	2037 (F)	1st	2037 (F)	-
Road Inno + Lock No Inno	-	2032 (F)	1st	2052 (T)	1st
Road Inno + Lock No Inno	Road Lanes2	2057 (F)	1st	2052 (T)	1st
Road Lanes + Lock No Inno	Road Lanes2	-	1st	2052 (T)	1st
Road Inno + Lock No Inno	Road Renovation	2036 (F)	1st	2052 (T)	1st
Road Lanes + Lock No Inno	Road Renovation	2043 (F)	1st	2052 (T)	1st
No Policy	-	2019 (T)	-	2034 (T)	-
Road Lanes + Lock No Inno	-	2037 (F)	1st	2052 (T)	1st

APPENDIX E – INTERVIEWS

E.1 INTERVIEW PROVINCE OF NORTH HOLLAND

Interview date:	05-04-2017
Person:	[redacted]
Function:	Asset Manager Province of North Holland
Subject:	Case study N23

After introducing the participants, the interview started with a short introduction about the thesis subject. The main aim of the thesis is to look at the strategic decisions to be made by asset owners for their asset system, based on long-term uncertainties. The uncertainties that will be evaluated within the research are climate change, economic growth and innovation. A problem regarding climate change that is most recognized within the province is the increase of precipitation, and consequently the increase of groundwater level. The research will test System Dynamics (SD) for quantifying and analyse the uncertainties. In the case study the N23 will be coupled (fictively) to the harbour of Amsterdam and the corresponding railway line will (fictively) cross the N23. In this case there is a tunnel that is connected to a sewer system of a municipality and lies under the railway line. The main view regarding the case study is during the design phase, despite the current project is almost at the end of its construction phase.

Q1 What were strategic decisions that have to be made within the N23 project?

The province communicates a set of requirements at the start of the project to the contractor. These requirements are based on standardisations. In this project the province had formulated the requirements in such a way that it formulate a much stricter requirement than prescribed by the standardisations. This is done because of the future uncertainties like road capacity and climate change. An example is that the requirements for the road dimensions were set much larger than prescribed by the standardisations, in order to assure sufficient capacity for possible future traffic flow increase. The standardisations are formulated in the ERBI (*Eisen en Richtlijnen Bouw-en Infraprojecten*). Additional to the ERBI, requirements are adapted to prescribed performance levels by Rijkswaterstaat (like % availability of the road). The roads were designed for 30-50 years and the other objects for a lifecycle of 100 years. Despite the fact that in the standardisation a lifecycle of 80 years is prescribed for the objects, the province prescribed a lifecycle of 100 years in order to delay future investments due to the changing environment. The design is thus made more robust than prescribed by the ERBI. SD could possibly help with grounding these decisions.

Q2 What where issues in the design of the N23?

There were be held a lot of expert meetings for choosing the appropriate tunnel material. The tunnel could either be constructed in concrete or in geotextile. The province preferred the concrete option because of the lower maintenance costs and risk during operations phase. The contractor preferred geotextile because of the lower construction costs.

A second design issue was the construction of the noise barriers. These were initially designed as a full glass construction. But, in order to best perform maintenance (mowing the grass). A 1 meter bottom layer of concrete was added to the noise barrier design. Those issues are solved in the design in order to assure sufficient maintenance.

A main challenge in the design was determining the alignment of the N23. The amount of stakeholders and ensuring sufficient limitation of environmental impacts were the main aspects that made these track design a complex issue.

Q3 I think main issues within the N23 are road dimensions and pump capacity of the tunnel, could you advise me regarding data for those issues?

In the ERBI are precipitation graphs available for designing the pump capacity. You can use those in case you are designing the pump capacity. Pumps are not that expensive during construction but there is more work to do in the maintenance phase. The amount of reservoir in the pump basement is much more important because this determines the pump capacity and the amount of pumps needed. Initially there will be used two pumps in case one pump does not function anymore. In the case of rail traffic above the tunnel, you need to contact PRORAIL.

Q4 What are aspects that are designed in such a way that it is beneficial during maintenance?

There need to be continuous access to the pump basements without harming the traffic. The basements are designed in such a way that this access is ensured. There are also at any time two pumps required in order to assure continuous performance of the pumping system. The pumps are monitored externally by continuous monitoring. The province always takes into account the limitation of maintenance costs when drawing up the functional requirements.

Q5 Has there been looked at climate change and/or innovations?

No, there is (in general) too less attention paid to climate change and innovations. The ERBI is based on future climate scenarios. The last version is from 2006. We use the ERBI, so in that way we are anticipating on the future scenarios. Also robust design is used in order to assure changes in precipitation and extreme/intensive precipitation.

Q6 What are aspects that you think I could integrate in my model?

It can be a good idea to look at the increasing groundwater level effects. Also the type of road traffic is changing. More heavy transport will use the road in the future. We currently use the guidelines like the Eurocode, but these are not including future growth and intensity of heavy traffic. Innovations that you could look at are the possibility for energy charging in a road deck, solar panels on noise barriers and Automated Driving.

Q7 How is the maintenance schedule determined?

This is prescribed in a IHP (*instandhoudingsplan*) which is focusing on 25 years. The lifecycle of the construction is longer than the 25 years so the IHP is adapted continuously based on new insights and experience. Maintenance is based on prescribed lifecycle requirements in the design. In choosing maintenance moments the preferences of different stakeholders are combined. A maintenance moment for a road is for example used to perform maintenance on the noise barriers. The requirements set in the contracts are minimal requirements and the contractor is thus challenged for making innovative ideas that assure longer lifecycle of the assets.

E.2 INTERVIEW ANTEA GROUP (1)

Interview date: 10-05-2017
Person: [redacted]
Function: Senior Advisor (Antea Group) / Lector (Saxion)
Subject: Strategic Decision-Making

Question subjects: Strategic Decision-making, Adaptive Pathways, Scenarios Delta Commission

The interview started with a short introduction about the thesis topic and the progress made so far. The main aim of this research is to improve large intervention decisions by making them more strategically. The general approach that will be used within this research is the adaptive pathways approach. The adaptive pathways approach includes uncertainty in decision-making. The uncertainty results from the multiple future effects resulting from scenarios the asset system is facing. The questions in this interview will be asked to get a better understanding of the practical use of the adaptive pathways approach and to gain more insight in the scenarios developed by the Delta commission.

Q1 What are, in your experience, tools/methods used to support the adaptive pathways approach?

The adaptive pathways were used in two cases; the “Twentekanalen” and “VONK (VervangingsOpgave Natte Kunstwerken) project”. In the VONK project, the main aim was to develop a practical approach to gain insight in the (functional and technical) lifetime of multiple barriers in the Maas. The approach that was used for developing the practical approach, was the adaptive pathways approach. Explicit (computer based) tools/methods were not used to develop the adaptive pathways. The main method used was to quantify the different policies and sell-by date of actions by expert judgement and sensitivity testing. In this regard, the scenarios drawn up by the Delta Commission were used. To determine the possible future scenario , the worst and best case were chosen according to the scenario boundaries. Computer based simulations were not used. The technical lifetime was easier to determine than the functional lifetime. The technical lifetime could (easily) be calculated by detailed calculations for the technical lifetime of the asset.

Q2 Regarding the adaptive pathways approach, what are, in your experience, the main limitations and complexities of this approach when having to take future developments into account?

The main complexity in this approach is to determine the functional lifetime of an asset in a given policy. The functional lifetime is different than the technical lifetime. The technical lifetime is to what extent the asset could fulfil its technical requirements and thereby support its main function. The functional lifetime is to what extent the asset could fulfil its function regarding the developments in demand of its function over time. Further difficulties were; to quantify the multiple variables over time and which aggregation level has to be chosen for analysis.

A first limitation of the adaptive pathways approach is that it is hard to determine the ambition level and its corresponding improvement measure. The ambition level is the maximal functionality an asset owner wants to achieve whit its asset system. This ambition level could be either establishing its current function or develop towards a new function. The ambition level strongly determines the performance requirements for the policies that are developed. In the adaptive pathways approach it was hard to visualize which measure was responsible for the improvement of the functionality of the asset in a given policy.

The second limitation is that it is hard to communicate for which stakeholder the developed pathways are relevant. Multiple stakeholders usually are involved in large infrastructure asset systems, which makes it difficult to determine which stakeholder is responsible for implementing the developed policies.

Q3 What should be characteristics of a method that supports the adaptive pathway approach (and strategic decision-making) while taking into account the before mentioned limitations?

The first characteristic that a certain method should possess is that is should give insight in the future developments of the functionality of the asset. In other words: it should provide clarity about the functional lifetime of the asset in its changing environment. As a second characteristic it should include the influence of other asset systems in the environment of the asset. Asset systems have multiple interfaces and thereby affect the functional lifetime of the individual assets. The third characteristic should be that the tool/method provides insight in the stakeholders that are the owners of the different asset systems. The tool should stimulate the stakeholders to cooperate and to develop a shared policy for the asset on a system level instead of object level.

Q4 What are the main scenarios used by the Delta-Commission? How are these scenarios determined?

The scenarios drawn up by the Delta Commission were used in the VONK project. These scenarios combine socio-economic developments and climate change into four scenarios. The climate scenarios from the KNMI and the socio-economic scenarios from the WLO are used as input. The scenarios that best could be used for this thesis are the scenarios used by the Delta Commission in their latest report. The latest report could be downloaded from their website.

E.3 INTERVIEW ANTEA GROUP (2)

Interview date: 21-06-2017
Person: [redacted]
Function: Traffic Engineer
Subject: Road Model

The interview starts with a short presentation of the thesis topic, and introduction of the road model. The main topic of the questions in this interview is about the road model and its possible dynamics.

Q1 How are road models, in general, set up?

The viewpoint within road modelling is based on a network approach. Individual roads are always parts of a larger network. Interventions on an individual road impose effects on the network, and vice versa. The main objective of traffic modelling is to find the bottlenecks in the road network. The bottlenecks have to be adapted first, then the effects are modelled on the network to visualise the effects of the bottleneck adaptation. A network approach is important because solving only bottlenecks leads to congestion problems on other weak links in the network.

Intensities for the road network are determined by the amount of cars, and trucks that are using the network. The amount of cars, and trucks can be expressed in PCE (Person-Car Equivalent), or MVT (Motor Vehicle). PCE is determining the amount of cars, and trucks on a road network by using a relation factor between the size of a car, and a truck. The standard value of this relation factor is 2. MVT is determining the actual amount of cars, and trucks. Intensities are usually calculated for rush-hours, or per full-day.

Capacities differ per road type, and characteristic. The characteristics like road speed, lane width, amount of lanes and road quality determine the capacity on that road. The capacities per road characteristic can be found in ‘Capaciteitswaarden Infrastructuur Autosnelwegen’, by Rijkswaterstaat.

Q2 How do traffic models contribute in making large intervention decisions for roads?

The main objective of decision-makers is to ensure the functionality of the road on the long-term. To ensure this functionality, roads are mostly designed for an I/C (Intensity divided by Capacity) value of 0,8. An IC value of 0,8 typically gives congestion problems. When a road network or bottleneck reaches an IC value of 0,8 , planning starts for intervening on a road network. The effects on the road per IC value are explained in ‘Capaciteitswaarden Infrastructuur Autosnelwegen’, by Rijkswaterstaat.

Q3 Do you have general improvements for the road model?

It is recommended to model the effect that congested roads lead to traffic divergence. Road users are usually choosing alternative transport types, when a road starts to become too crowded, and there are a lot of congestion problems.
It is also recommended to model the I/C value in your model sheet. This is because the IC value is the most important value, for which decisions are made.

Q4 What do you think of the usability of the VENSIM model for this purpose?

VENSIM is a very interesting software for modelling road networks. It could be beneficial to model the road model physically, and location specific (by using stock-flows).
Another extra implementation could be the use of the output of traffic models as input for the VENSIM model. In this way hybrid traffic models are coupled to a more dynamic software program.

E.4 INTERVIEW RIJKSWATERSTAAT (1)

Interview date: 24-05-2017
Person: [redacted]
Function: Senior Adviser Infrastructure Strategy
Subject: Strategic Decision-Making (Harbour)

Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

Question subjects: **Future Transport Developments / Harbour Model / Strategic Decision-making**

The interview started with a short introduction about the thesis topic and the thesis design. The main aim of this interview is to gain knowledge for strategic decision-making for ports and waterways. The answers in this interview are predominantly based on the port of Rotterdam and Amsterdam.

Q1 What are, in your opinion, the main developments regarding the future of ports, and vessel transport?

The main triggers for development in ports come from economic growth, and population changes. The bigger the population, the more is consumed, the more vastly a port develops (or vice versa). This can also be seen when the economy grows, or stagnates.

The geographic location of a port is equally important. The location can comply with what is needed, and what is produced at which specific location. It is fair to say that the streams of bulk through a port, are largely influenced by its geographic location.

Throughout the years, there has been an overall trend of vessels scaling upwards. The reason for this was that raiders saw bigger vessels as a cheaper way of transportation. However, this upward trend might stagnate somewhere in the future. This stagnation can be caused by a future increase in regional production. The Post Panamax class could very well be the biggest class ever, but you never know for sure.

Q2 What are, in your opinion, the main uncertainties regarding future port developments and vessel developments?

The main uncertainties regarding future port developments result from climate change, economic growth, and population changes. It is never entirely sure what will happen in the future. An example could be taken form the Maasvlakte 2. This artificial island was built with potential sea level rise taken into account. However, one meter extra in height would possibly have been better with the current available knowledge.

Climate change can cause the water level of waterways to be extremely low in summer, and extremely high in winter. With low water levels vessels cannot pass when fully loaded. Moreover, there are not enough vessels available to carry only half the bulk (smaller vessels). With high water levels problems can arise with vessels trying to pass crossing bridges.

Overall it is uncertain if vessels will keep increasing in size or that smaller ships will be able to handle the dominant regional production.

Q3 What are the main “large intervention decisions” that have to be taken in infrastructure asset management regarding the functional lifetime of ports and waterways?

When making large intervention decisions it is always very important to only consider long term developments, and steer away from short term fluctuations. It can be challenging to see the difference.

In terms of climate change, a decision-maker can arm a port 100% against climate change effects, or a decision-maker can shift to a different scope. The decision can be made to hold 100% availability for the ports infrastructure, or when changing the decisions scope, more storage area can be created for possible extreme weather events.

It is important to realize that arming against future developments is not always the same as adapting to them. In case the earth’s temperature rises, and the waterways become shallow, it might be more efficient to shift to trains or roads for transportation means.

Q4 What are, in your experience, the main tools/methods used in strategic decision-making, regarding the future developments of a harbour and corresponding transport flows? What are their limitations/benefits and complexities?

Traditionally, most decisions are made using scenarios. The main reason for this comes from the fact that they are easily explainable to a wide public. Explaining uncertainties to politicians and civilians can be very challenging, and scenarios can make uncertainties more insightful. However, scenarios should always be seen as a guideline, and not as a blueprint. This is a pitfall for most decision-makers.

Serious gaming is a relatively new tool, which is gaining popularity. This tool is most efficient in providing insight in possible decisions, and creating awareness.
Cost Benefit Analysis (CBA) is used to support decisions. The main problem with CBA is that positive values do often not reflect the available budget for the decision. The political discussion behind a decisions is normally more challenging than the result from a CBA.
The adaptive pathways method has been used on few occasions. The main challenge lies in finding insight in the many variables, and providing information. It is very difficult to make the right decision with so many input. It is important to keep models as simple as possible, otherwise it is difficult to find the cause of certain behaviour.

Q5 **To what extend does the possibility for harbouring the largest vessels in the world, increase a ports yearly distribution?**
Providing possibilities for harbouring larger vessels can increase the amount of regular distribution. It is however questionable if vessels will keep increasing in scale.

Q6 **Through what factors, does the functioning of infrastructure to a port, influence local economies, and the ports yearly distribution?**
When considering the port of Amsterdam it can be said that the possibility for harbouring larger cruise vessels can increase the local economy. Moreover, the port of Amsterdam has a higher potential of adding value to the local economy than the port of Rotterdam. This is because the harbour of Rotterdam mainly has transhipments. However, on social ground the port of Rotterdam unites its citizens, and has international status.
The functioning of infrastructure around a port is of great importance. An example can be taken from Australia, where cities are separated by great distances from ports. It can take a long time before products arrive at certain areas, which increases prices.

Q7 **What are in your experience, effective measures, against area shortage for harbours?**
One of the major effective measures is to reuse area more efficiently. Older inefficient parts can be replaced with state of the art technology. It is also important to realize that ports are never an independent functioning object, they have many dependent parts. It can therefor sometimes be better to fuse with other harbours. In the future it might be more efficient for the ports of Amsterdam and Rotterdam to fuse (or even Antwerp).

E.5 INTERVIEW RIJKSWATERSTAAT (2)

Interview date: 24-05-2017
Person: [redacted]
Function: Senior Adviser Asset Management
Subject: Infrastructure Asset Management

The interview starts with a short presentation of the thesis topic and research design. The main topic of the questions in this interview is infrastructure asset management and corresponding strategic decision-making.

Q1 What are, in your opinion, limitations in current infrastructure asset management regarding decision-making based on future uncertainties?

Traditional asset management is aimed at maintaining the current asset in its current function. This a static approach, because the function of the asset is considered to be static, it does not change dynamically over the technical lifecycle of the asset. In modern asset management a more system level and dynamic approach is required. The main reason for this is that there are future developments that can affect the function of the asset. So in other words: the function of an asset is not as static as it may be perceived.

Asset management is applied on different levels (network and operational). Operational asset management aims at maintaining the asset under its given function (short-term, reactive). Long-term scenario planning regarding the change in functionality of the asset is applied on network level. Different people, on different levels are involved in decision-making based on future uncertainties.

It is difficult to interconnect different future scenarios (population, economic growth, climate change) ,and to obtain information about the future effects of these scenarios for the asset. Infrastructures are designed for long technical lifecycles (e.g. 100 years), the future requirements and conditions of these infrastructures is very uncertain.

Decisions have to be made in a political environment. In this regard it is sometimes unclear on what basis decisions are made ,and the view of decision-makers changes over the lifecycle of the asset. The model should therefore provide the right information for a decision-maker, on which a decision-maker can base its political decision.

Q2 In current asset management, how is the "intervention moment" stipulated for which intervention decisions are made? Are these intervention moments mostly based on the technical lifetime, or functional lifetime?

In the past most intervention moments were based on the change in functionality of the asset. These changes occur at a network/regional level, not at the level of an individual asset. A change in functionality of the asset system mostly includes a change of the asset system or building a new asset system (realization projects).

These decisions were mainly based on the functional lifetime of the asset (e.g. capacity of a bridge).

The current expectations are that in the future there will be less interventions based on functional lifetime (resulting from changes in functionality of the asset on network level), but more on technical lifetime. This includes that there will be more focus on maintaining the current asset than building a new asset. Maintaining the technical functionality of the asset becomes more important.

The technical lifetime will determine the urgency for building a new asset ,and stipulates the intervention moment. The functional lifetime of the asset is analysed from this "technical" starting point. The problem starts on object level (bridge) ,and is then translated to a higher aggregation level (corridor) by analysing the functional lifetime.

In general 90% of current replacement decisions for structures are made on basis of functional lifetime, in the future this is expected to be 50%. Replacement decisions for structures are just a small number of the possible decisions that are made. Technical lifetime is mostly extended until maximum costs are reached, or until the functional lifetime is exceeded.

Q3 How are the influences of a single object (e.g. bridge) on the asset system (e.g. road system) incorporated in asset management decision-making?

The main effects can be foreseen by sufficient scenario planning and object-oriented models. In long-term scenario planning it is recommended to have an integral view in an early stage. The object oriented models are used to analyse the objects functional lifetime, which is then translated into the lifetime for the asset system on a higher aggregation level.

Rijkswaterstaat aims at gaining insight in the technical lifetime of the infrastructure objects, and corresponding environmental effects in the earliest stage of the process which ultimately leads to decision-making regarding the replacement/renovation/rehabilitation of a structure. In reality this means a time horizon of ca. 15 years. This will influence potential scenarios to deal with the issue of end of life. Sometimes these interventions are recognized to late, which induces large costs and changes in scope.

Analyses on a high aggregation level are recommended in order to assure that there will be no double interventions in the same area ,and that effects of/on different asset systems are incorporated. This includes that the analyses are made on network level ,and then translated to operational level. This approach ensures cooperation with all relevant stakeholders in the asset's area. It is often difficult to translate the long-term plans made on network level to activities on operational level.

Q4 What are, in your experience, the main tools/methods used in strategic decision-making (based on functional asset lifetime) within infrastructure asset management?

The asset's functional lifetime is hard to determine because of the large bandwidths that are involved in the scenarios. Currently there is no standard tool for determining the functional lifetime of an asset.

For determining the technical lifetime of an asset there are plenty of tools available (e.g. LCC (Life Cycle Cost Analysis)), but these tools are often object oriented and static. Another example is the PROBO approach (including FMECA, FTA), which is based on failure of the asset under a static function. The approach has a long-term view, but is not able to make a long-term prognosis. Long-term prognosis can be made when limitations (like a static approach) are accepted, which enables a more in-depth analysis and reduces uncertainties of the outcome. Or when there will be tried to involve a lot of future uncertainties, which eventually ends up with a large bandwidth.

Decision-making on a higher aggregation level includes making use of tools like CBA (Cost Benefit Analysis) ,which is used to incorporate the effects on society ,and other asset systems / stakeholders in the environment of the asset.

It is hard to determine the 'tipping point' of an asset's functional lifetime. The end of lifetime of an asset is the result of a decision, and not a definite point in time'; knowing the exact point is not required, it is more important to know the period in which an asset reaches its functional end-of life. Exact budgets are determined at the latest stages of a project, ideally 5 to 10 years is planned forward in renovation and replacement projects. In realization projects this planning period is longer, this also depends on the aggregation level at which the intervention takes place.

Q5 In the previous question you mentioned that the pragmatic moment based on the reservation of budget is 2030, is this moment the maximum level for which decisions are made?

Most prognoses of renovation and replacement needs are made until 2050. These prognoses often include financial analyses ,and are based on statistics.

Short-term projections (5 – 10 years) can be made on basis of facts (e.g. results from a technical Inspection and are often applied in renovation projects. Long-term projections are often based on statistics and prognoses.

Future projections in 2100 (e.g. for climate change) are only considered at realization projects, this is because infrastructures are designed for long lifecycles. The urgency is mostly for short-term projects, these have the largest attention. The challenge is to couple the long-term perspectives to short-term urgency.

E.6 INTERVIEW BAM PPP

Interview date: 09-06-2017
Person: [redacted]
Function: Project Director BAM PPP
Subject: Strategic Decision-Making

The interview starts with a short presentation of the thesis topic and research design. The main topic of the questions in this interview is planning of infrastructure and corresponding strategic decision-making. The first part of this interview will consist of questions related to BAM PPP. The second part of this interview will relate specifically to sea lock IJmuiden.

Part I BAM PPP

Q1 **How often does BAM (PPP) face long term decisions within projects, were insight in uncertainties as climate change, and economic growth is necessary? Until what extend are these uncertainties incorporated during decision-making?**

The contractual position of BAM PPP mostly considers contractual/financial protection for all risks in terms of future uncertainties. If uncertainties as climate change do happen, BAM PPP does not want to be responsible for its consequences. In the past, volume contracts were used. Within these contracts payments are made for the total amount of volume that uses the infrastructure. This contract is not used in the Netherlands any more since it hold large risks, and can results in big losses.

Most contracts used today, state that contractors need to provide technical availability. Therefor most contractors look at providing only technical availability, and diverge risks for future uncertainties to different parties.

In some projects, BAM PPP does use climate change scenarios. This is mostly performed on energy projects (building PPS projects). However, in these projects, the risks resulting from climate change are again shifted to different parties. The client determines which scenario have to be used.

Q2 **What are, in your opinion, the main challenges when making decisions within long-term projects that are subjected to future uncertainties?**

The main challenge is to find a flexible relation with public authorities (clients), in which it is possible to pivot when changes occur. The contractual mechanism that is used now, is sufficient for providing this flexible relationship. The challenge lies in dividing benefits/risks in good harmony.

BAM PPP is looking into Big Data. The goal is to perform studies about past project, through which clients can be advised on possible uncertainties for future projects.

Q3 **What are, in your opinion, the main limitations when making decisions within long-term projects that are subjected to future uncertainties?**

The main limitation for BAM PPP, is to get acceptable risks from the client. Through which BAM PPP arms itself against the majority of uncertainties.

Q4 **What are, in your experience, the main tools/methods used in strategic decision-making based on future uncertainties? What are their limitations/benefits and complexities?**

BAM can win a contract by scoring higher on the predefined EMVI criteria. Within the EMVI criteria, long term uncertainties are taken into account. The predominant tool used, is the Trade Off Matrix. This tool compares all scores, for all criteria, in a static manner. To compare the scores with the actual scores that the client will give, conversations are held with the client.

Part II Sea Lock IJmuiden

Q5 **How are future uncertainties incorporated in the design/construction of the sea lock of IJmuiden?**

The main part of the lock coming to mind, is the flood protection system of the lock. RWS contractually asked for a minimal height of the flood protection system. The flood protection of the new sea lock is already higher than all its surrounding structures. BAM PPP designed the flood protection as high as possible, and also adaptable to bigger heights in the future. This ensured a higher EMVI score.

Q6 **What where the most important considerations made within the EMVI criteria for the sea lock of IJmuiden?**

One of the most important considerations with regard to economic growth was the width of the lock. We had to calculate what an extra 5 meters of width would contribute and cost. However, the client is the party most responsible for steering the project by defining the EMVI criteria.

Q7 **What were, in your opinion, the main risks for the old sea lock of IJmuiden regarding future developments? How does the new sea lock cope with these challenges, and what future challenges will it have to face?**

During the war, the old sea lock was hit by a bomb. Therefor the old lock is less robust and could become unstable. When constructing the new lock, next to the old lock, this could cause risks (deforming, collapsing).

Q8 **The sea lock of IJmuiden will be the biggest sea lock in the world. Do you think locks can be made even bigger, given technical limitations? And how much bigger in terms of capacity?**

Technical limitations are there to be broken. It will probably always be possible to construct even bigger locks. However, at some point there is an optimum between the size of the lock and the amount of water that has to be pumped. To pump such big amounts of water is very time consuming. The question is how efficient it would be, to make a lock even bigger. It might be more efficient to build multiple lock next to each other, with a considerable size.

Q9 **In a high economic growth scenario (2%), it is estimated that the current lock complex (with the new sea lock) will reach its maximum capacity in 2026 (125 million tonnage per annum). Given the fact that this world offer can grow to 170 million tonnage in 2047, what possibilities are there to accompany this growth (given the limited space)?**

Yes these possibilities are there, the probable limitation will be the NZK. It might even be possible that TATA Steel frees its area partly, depending on steel market developments.

Q10 **The Noordersluis has a technical life expectancy until 2029, it could be a possibility to renovate the lock for future use. How long would it take to renovate this lock, and how much would it increase the locks capacity?**

It is possible to renovate the old lock, the amount of capacity added is hard to define. The most important risk for the authority regarding renovating the Noordersluis, or adding other locks, is “zoutbezwaar”. The NZK flows into the Ijsselmeer, which provides most of the drinking water for the Netherlands. If too much salt water intrudes, this can affect the drinking water. This could be solved by pumping back seawater with big inlets, after a vessel enters the NZK. However, this new technology is not yet proven.

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Delft Delft University of Technology

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