# Multivariate simulation modelling for adaptive long-term infrastructure planning

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Q1

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# Q2 Multivariate simulation model for adaptive long-term infrastructure planning

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**Infrastructure asset managers are challenged by rapid changes around the world such as urbanisation and climate change. They have to deal with multiple complex and dynamic infrastructure systems that can influence each other and that can be influenced by various uncertain factors. Traditional planning methods are not well suited to complex and dynamic infrastructure environments. However, there are various alternative methods that can be used. This paper presents a simulation model for adaptive long-term infrastructure planning. For this model, a combination of planning and simulation methods is used that can cope with complex and dynamic (infrastructure) environments (i.e. system dynamics, exploratory modelling and analysis and adaptive pathways). This methodology is illustrated with a case consisting of a road system and a lock system in the Netherlands. The approach should be tested further in other cases, but it shows promise in improving the support of infrastructure decision-making in a complex, dynamic and uncertain infrastructure environment.**

## Introduction

Cities all over the world are rapidly transforming, while their infrastructure networks are not always resilient to these future developments. Some cities transform into megacities, as is the case with cities in Brazil, India and China. These cities have experienced a large population growth in a small period of time, and their infrastructures cannot accommodate these growths (Taudenböck *et al*., 2012). As the world population is still growing, the transformation of cities into megacities can be expected to continue on the global scale. The opposite behaviour can be witnessed during counter-urbanisation, which causes significant population declines. Counter-urbanisation can be caused by economic contraction (UN Desa Population Division, 2016) and natural disasters such as Hurricane Katrina, which hit the city of New Orleans in 2005 (UN Desa Population Division, 2016).

Developments that have large influences on infrastructure performance can be caused by changes in climate, economy and urbanisation, as well as innovations such as automatic driving and intelligent transportation systems, which affect the amount of road users and require a different approach for the information exchange between roads and cars (Milakis *et al*., 2017). Developments in climate change can affect the technical lifetime and consequently the performance of infrastructure systems (IPCC, 2014; KNMI, 2015). Economic growth can affect traffic intensities (Manders and Kool, 2015), while urbanisation and de-urbanisation affect the city populations and can require different land uses (UN Desa, 2014).

To adapt infrastructure systems to these future developments, infrastructure asset management is applied (Hastings, 2014). Infrastructure asset management is a coordinated activity of an organisation which aims at optimising the performance of infrastructure asset systems, during their whole life cycle, by balancing of costs and risks (IAM, 2015). Infrastructure asset management aims at infrastructure performance optimisation by applying long-term planning for large interventions. Large interventions are adaptations to the infrastructure system with the aim to increase the performance of the system, such as expansions, renewals and large renovations (Hastings, 2014).

Future developments that affect infrastructure asset performance have a dynamic, complex and uncertain character. The specific conditions of an asset can change dynamically over time for a multitude of reasons. Further, infrastructure asset systems are complex systems due to the many feedbacks between different system elements. They can perform multiple functions on different scales and influence each other due to their local proximity or dependencies (Bhamidipati *et al*., 2016). Finally, developments in, for example, population growth or future precipitation levels are known to be deeply uncertain (Lempert *et al*., 2003).

Dynamic complexity and uncertainty can affect the performance of an infrastructure asset system. As optimising the performance of an infrastructure asset system is the main aim of asset management, asset managers require reliable insight into the system's behaviour. In order to be able to apply long-term planning strategically for their large interventions, multiple variables and their underlying relations need to be incorporated. However, in current asset management practices, asset managers base these long-term plans on decision-support methods, which provide insufficient insight into the dynamic complexity and uncertainty to which infrastructure asset systems are subjected.

The main challenge for decision makers within infrastructure asset management is to develop a shared policy in which all relevant stakeholders from different infrastructure systems are incorporated when dealing with dynamic complexity and uncertainty. From interviews held for this research, a number of challenges have been identified. These challenges originate in operationalising of the interventions, the complexity of asset systems and uncertainty regarding future developments. On the operational level, misinterpretation of the effects of an intervention creates insufficient performance of asset systems. The complexity of asset systems makes it challenging for asset managers to incorporate all variables and underlying relations in order to be able to consider both the technical and functional lifetimes for all the multiple functions of an asset. Finally, uncertainty in the magnitude and time of occurrence of future developments often leads to asset managers overestimating these future developments by applying too large bandwidths or solely design for the worst case. In this case, uncertainty often leads to overdesigned interventions and corresponding unnecessary costs. In general, there is a tendency for asset managers to ignore the adverse impacts of large uncertainties because of solution aversion (Campbell and Kay, 2014). In the perspective of multiple stakeholders, the issue of, for example, climate change effects can be ignored or admired.

Arguably, these challenges are related to the static nature of current decision-support methods, which often consider single sector infrastructures and one event or scenario of events with the highest probability of occurring (Bhamidipati, 2015). Therefore, it is of interest to find a decision-support method able to incorporate all relevant dynamically changing complexity and uncertainty.

In this paper, the authors applied a combined method able to incorporate all relevant dynamically changing complexity and uncertainty. The method is of a dynamic nature and was applied to a case study which consisted of multiple interconnected infrastructure systems subjected to future uncertain events that changed dynamically over time. Furthermore, this paper found that the method can be applied for shared policymaking and considers the technical and functional lifetimes for all the multiple functions of an asset.

This paper is structured as follows: subsequent questions that will be dealt with in this paper are (*a*) which decision-support methods can be used to be able to incorporate dynamic complexity and uncertainty in policymaking, (*b*) which results can be obtained by a multivariate support tool and (*c*) how can these results be used to improve decision-making within the long-term planning of infrastructure asset management plans? In the section headed
**Q4** 'Methodology', the authors introduce the decision-support methods used in their case study. In the section headed 'Results', the results are presented, and finally, the conclusion of the authors' research is presented.

## Methodology

### Goal

The goal of this research is to develop a robust set of intervention policies for a set of interconnected infrastructure asset systems. The authors use the dynamic adaptive policy pathways (DAPP) **Q5**
approach (Haasnoot *et al*., 2013) combined with a system dynamics (SD) model (Forrester, 1961; Sterman, 2000) and simulations with the exploratory modelling and analysis (EMA) approach to achieve **Q6**
this goal. In this section, the authors explain the adaptive pathways approach, EMA, SD and their model of the interconnected infrastructure systems and provide the experimental set-up.

### Dynamic adaptive policy pathways

DAPP is an approach which is aimed at providing decision makers, such as infrastructure asset managers, with a plan which is both robust and adaptive to the way that the future unfolds. Robustness is aimed at finding intervention measures or policies that function desirably independently of how the future unfolds. A common way for decision makers of dealing with deep uncertainty is to try and find an 'adaptive' policy. A good example of such an adaptive policy is coupling the retirement age to the life expectancy (Auping *et al*., 2015). However, in the case of infrastructure assets, this is not possible, as most interventions are static in nature. This is not because the interventions themselves are static, but that they are primary based on static tooling. With static tooling, it is impossible to prepare a dynamic policy plan. DAPP solves this issue by sequencing actions for potential interventions and by making potential lock-ins and path dependencies explicit in adaptation pathways maps. A general example of an adaptation pathways map is shown in Figure 1. These maps show all possible actions, showing crucial tipping points between the actions in relation to a timescale. The different options are also scored in relation to costs, target effects and side effects.

SD is a simulation modelling method that aims at understanding the time dynamics of systems by simulating their structure. SD uses 'stocks', 'flows' and auxiliary variables for this, where each stock is an integral equation of all inflows minus all outflows. SD models thus form large structures of interconnected integral equations, which can be solved through simulated time by using numerical integration methods. The integral equations make the use of SD particularly suitable for those systems in which feedback, accumulation and delays play an important role, as is the case for most infrastructure asset systems.

EMA can extend the use of computational models by generating tens of thousands of scenarios in view of exploring and analysing this ensemble of plausible futures and testing the robustness of decisions in the entire uncertainty space (Bankes, 1993). These simulations were performed with the EMA workbench and are based on the computational SD model and programming language. In this manner, the SD and EMA method were combined. The combination of methods is named exploratory system dynamics modelling and analysis (ESDMA) (Kwakkel and

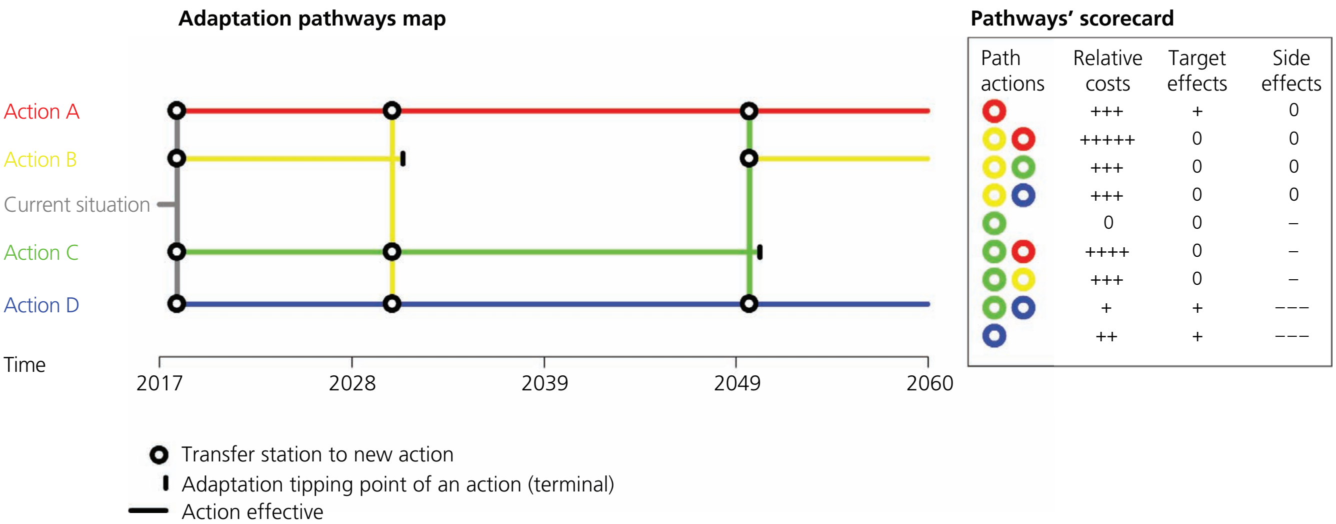


Figure 1. Example of an adaptation pathways map (left) with a scorecard for options (right) (adapted from Haasnoot *et al.* (2013))

Pruyt, 2015). Applying the ESDMA approach is beneficial because of the opportunity to extend the SD model with a simulation program (EMA) that is able to perform tens of thousands of simulations and generate subsequent scenarios. Furthermore, within EMA there are more visualisation possibilities.

## Use of methods in this study

In this study, the ESDMA method is used in order to find adaptation pathways. This combined approach is applied within the long-term planning of large intervention decisions for infrastructure asset management. An SD computer model was built that provides a representation of the dynamics within the case study and its accompanied infrastructure systems. The computational model was subjected to future uncertain developments, which were simulated with the EMA approach. The model and its underlying equations can be found at GitHub (2019).

Next, the results of the ESDMA analyses were incorporated into adaptation pathways with the adaptation pathways approach. This is done for a case study focusing on the overall decision support for adapting long-term planning of large intervention decisions to dynamic complexity and uncertainty.

## Case study

This section describes the set-up of the case study. It should be emphasised that the case study and its details are purely a demonstration of the concept that is used: a dynamic modelling approach for adaptive long-term infrastructural and multilinked civil engineering asset network planning. For that reason, not all case-specific details and numerical results are presented in this paper and the results and conclusions are primarily geared to the approach rather than to the case specifics.

As a case study, a schematised representation of the city of Amsterdam (the Netherlands) and its surrounding infrastructure systems was used. This case is relevant, as several large interventions are planned close to Amsterdam to ensure the technical and functional performance of a multifunctional lock and road system. The authors built an SD model of the combined Amsterdam–IJmuiden region. The model allows simulating how the intensity over capacity (I/C) factors of the Amsterdam road and lock systems will dynamically change over time and analyse which uncertainties and structures are responsible for problematic situations. The details of the case-specific input data can also be found at GitHub (2019).

The model consists of six main subsystems (Figure 2). The city subsystem represents the city of Amsterdam with its population, housing and business area. The city is situated in an 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 (Municipality of Amsterdam, 2011).

The harbour subsystem includes the port of Amsterdam with its distribution flows. Currently, the port of Amsterdam is the fourth largest harbour in Europe, with a constant need to expand (Port of Amsterdam, 2015). It is connected to multiple infrastructure asset systems and is an important contributor to the local economy.

The area subsystem represents the Amsterdam–IJmuiden region with all relevant city and infrastructure aspects. A limited amount of area is available through which the area subsystem performs a pressure on the other subsystems.

The economy subsystem is a representation of the local economy of Amsterdam. The local economy is influenced by exogenous as



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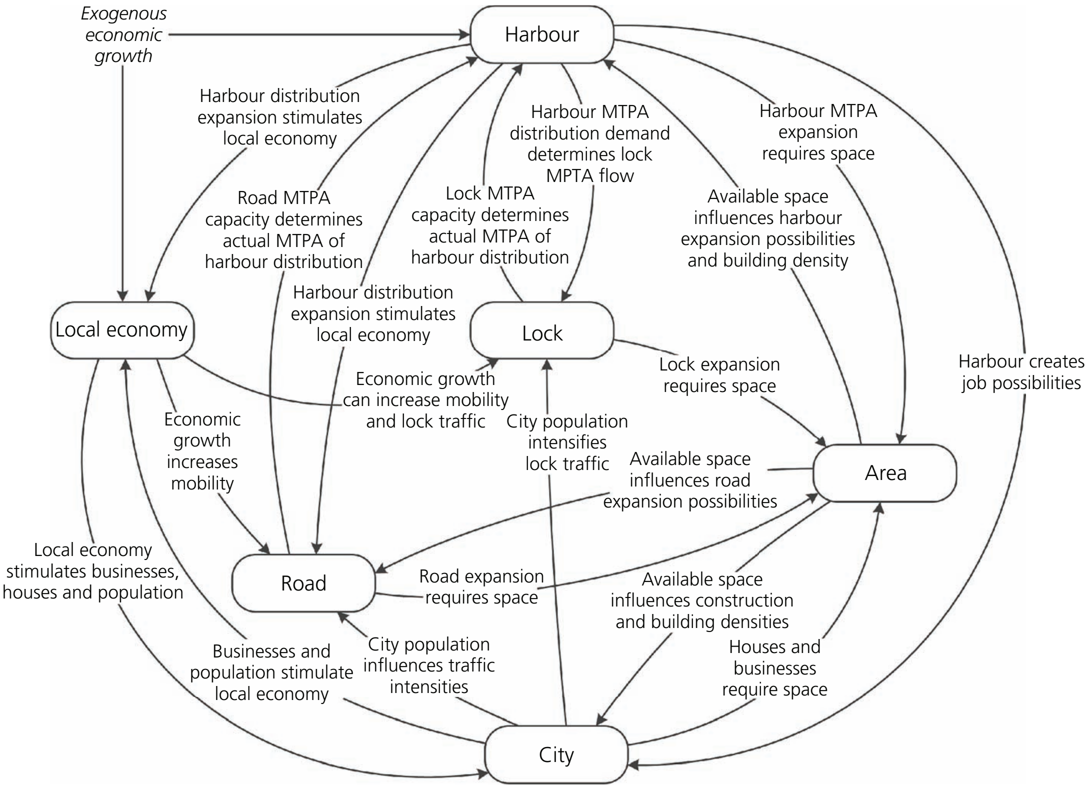



Q7 Figure 2. Subsystem diagram of the SD model. Each subsystem is depicted in a box; relations between subsystems are indicated on the arrows between the subsystems. Important exogenous influences are in italics

global macroeconomic growth. Furthermore, endogenous factors such as the performance of infrastructure and the amount of businesses, houses and population can influence the local economy dynamically over time.

The lock subsystem schematically represents the lock complex of IJmuiden. 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 be finished in 2022 (Port of Amsterdam, 2018). More interventions might be required in the future if the harbour’s demand keeps increasing. 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 and sea level rise.

The road subsystem represents the major road network surrounding the city and main distribution routes from the harbour and the lock including the IJmuiden lock complex. 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.

The model was extensively verified and validated to test whether it is fit for purpose. The authors first checked whether the units of all equations matched. Second, partial model tests were performed on each separate subsystem. Third, direct structure tests were performed, aimed at testing whether the structure model makes sense without simulation, by expert interviews and consistency checks with the literature. Fourth, the authors checked whether all runs performed with the models were within physically possible bounds. Fifth, structure-oriented behaviour and behaviour reproduction tests were performed to compare run behaviour with real or anticipated behaviour.

The conclusion of the verification and validation tests was that the model is of sufficient quality to use for the Amsterdam case. The authors also found some limitations: the model is not constructed on geographical dependency. The submodels are not dependent on their specific location within the total area. Furthermore, the rail and canal were not included in the model as specific submodels. The rail and canal were integrated in the harbour model, by which they provide only a restriction on the harbour distribution capacity and not on the capacity of the rail and canal infrastructure itself. Therefore, these models also do not have a restriction in land use. However, the use of the model as described in this paper remains within the plausible bounds.

### Experimental set-up

The authors performed 1000 experiments with their model using the EMA workbench release 1.0.0. The experiments were generated by Latin hypercube sampling over 34 uncertainties. The model was simulated between 2017 and 2060 in the Vensim software (Vensim DSS for Windows version 6.4E) with a time step of 0·0039 0625 year and the Euler integration method. The results of the ESDMA analyses, the underlying equations and input data can be found at GitHub (2019). At GitHub, a model summary is provided as an html file ('FinalModelEMA-MGA.html'). The internal relations within the model are primary based on expert judgement. The accompanied uncertainty is simulated by applying bandwidths on the variables. The bandwidths are mostly based on literature and or assumptions from practice.

## Results

### Complex infrastructure network under dynamic uncertainty

First, the dynamic uncertainty subjected to the complex multifunctional infrastructure asset systems was assessed. Asset managers perceive it as challenging to gain insight into 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. Therefore, interventions are often overdesigned, which can lead to unnecessary costs.

Therefore, the key performance indicators (KPIs) on which asset managers primarily base their intervention decisions had to be presented dynamically over time. This is presented in Figures 3 and 4. The KPI for the road and lock system is the I/C factor. The I/C factor of the IJmuiden lock is mainly dependent on the amount of macroeconomic growth (Figure 3). The increase in demand from the harbour, which is strongly related to the macroeconomic growth, increases the intensity of vessel flow through the lock. Figure 4 shows an increase in I/C between 2027 and 2036, related to the end of the technical lifetime of the lock. The actual closing date is dependent on climate change scenarios and breakthroughs in innovation. Both Figures 3 and 4 show a decrease in the I/C factor around 2020, caused by the opening of a new separate lock in the entire lock complex. The actual opening date depends on the construction time (with possible delays).

The I/C factor of the road is, similar to 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

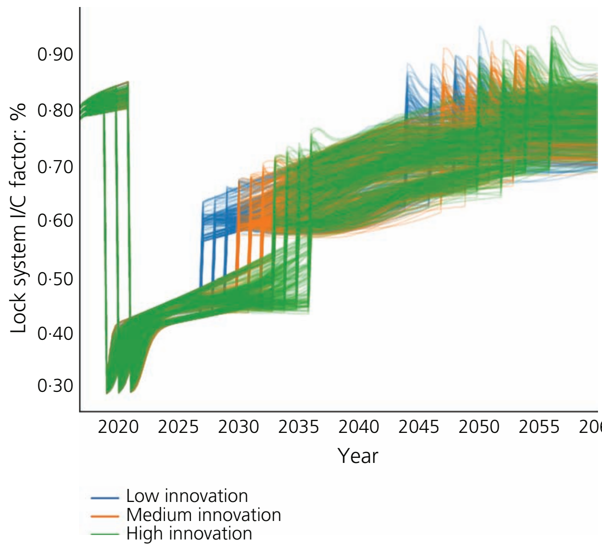



Figure 4. Lock system I/C factor divided by innovation

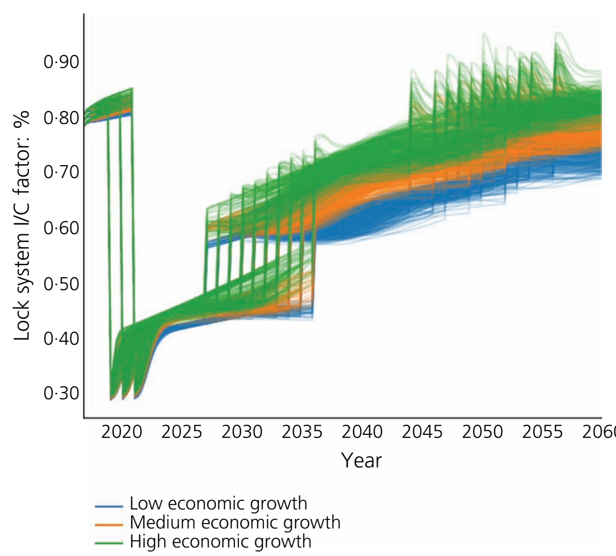



Figure 3. Lock system I/C factor divided by economic growth

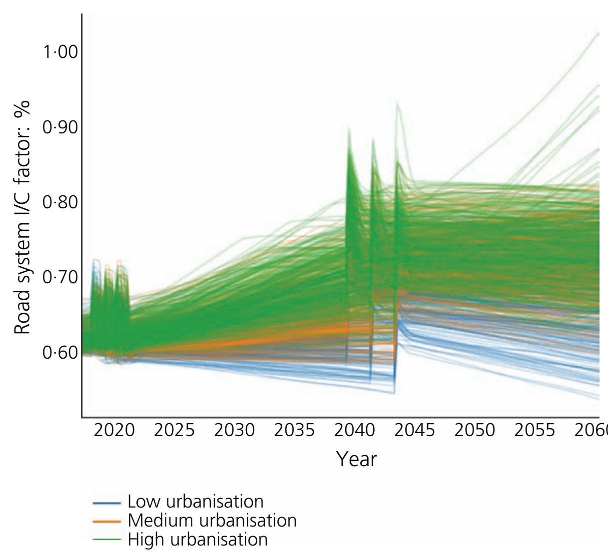


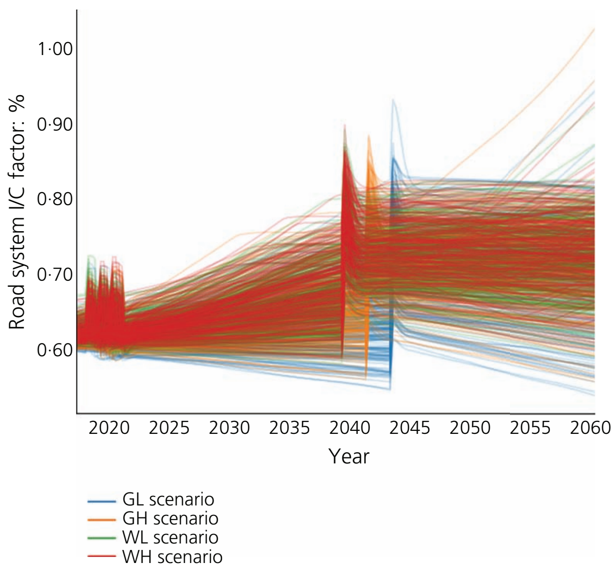

Figure 5. Road system I/C factor sorted by urbanisation

population, indicated by urbanisation (Figure 5). The higher the urbanisation scenario, the bigger the chance for high traffic intensities. The road will reach its end of technical life at about 2040, but the exact moment depends on the climate scenario (Figure 6). Moreover, high climate scenarios cause higher I/C values until the end of simulation; this mainly results from deterioration and sewer overflows.

## Dynamic complexity of infrastructure systems

Second, the interconnectedness of infrastructures was assessed. Infrastructure systems are interconnected 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 the network to the operational level, with so many variables and underlying relations involved. This leads to the misinterpretation of the effects of an intervention and thus creates insufficient performance of asset systems.

Therefore, interventions were implemented on the network level, and the effects that these interventions had on other asset systems and sectors were measured on the operational level. This influence of interventions is shown in Figures 7 and 8. The authors performed simulations in which the influence of the infrastructure asset systems could be powered on or off. In an unconnected simulations, the infrastructure asset systems had to bear the maximum traffic intensities (light blue colour). When the infrastructure asset systems are connected, they can limit one another (light orange colour). When both the unconnected and connected simulations overlap, a dark green colour is presented. In Figure 7, 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




Q8 **Figure 6.** Road system I/C factor sorted by climate change

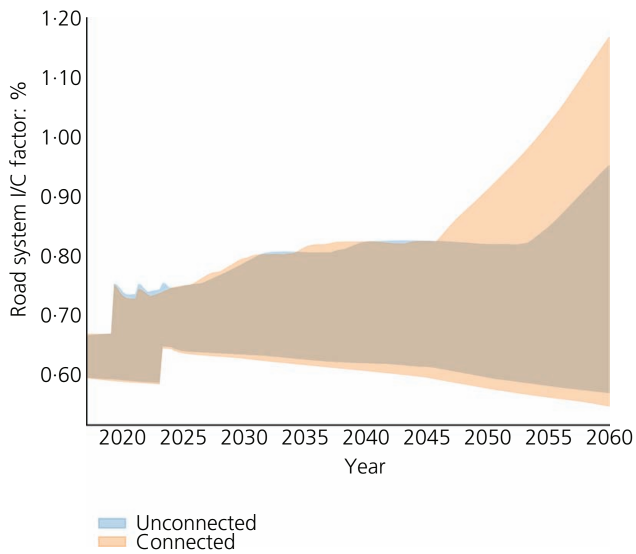



**Figure 7.** Road system I/C factor sorted by connected or unconnected infrastructure systems Q9

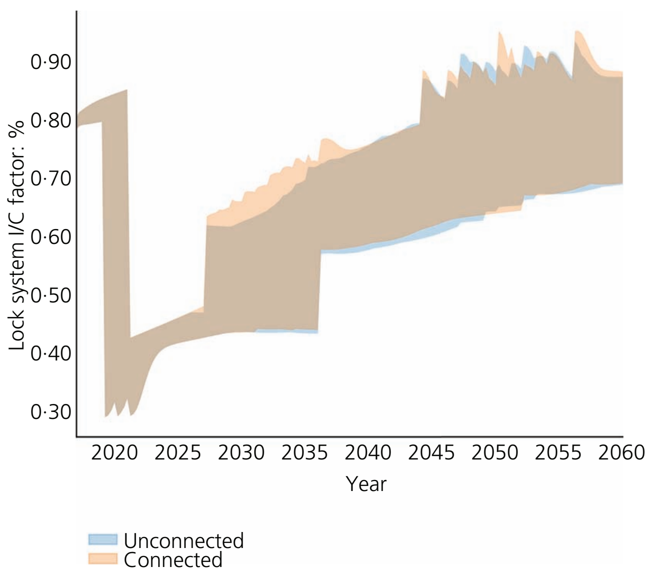



**Figure 8.** Lock system I/C factor sorted by connected or unconnected infrastructure systems

harbour demand and consequently vessel intensities through the lock. In Figure 8, 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 orange, more brown). In other words, the intervention on the road system increases the vessel flow through the lock.

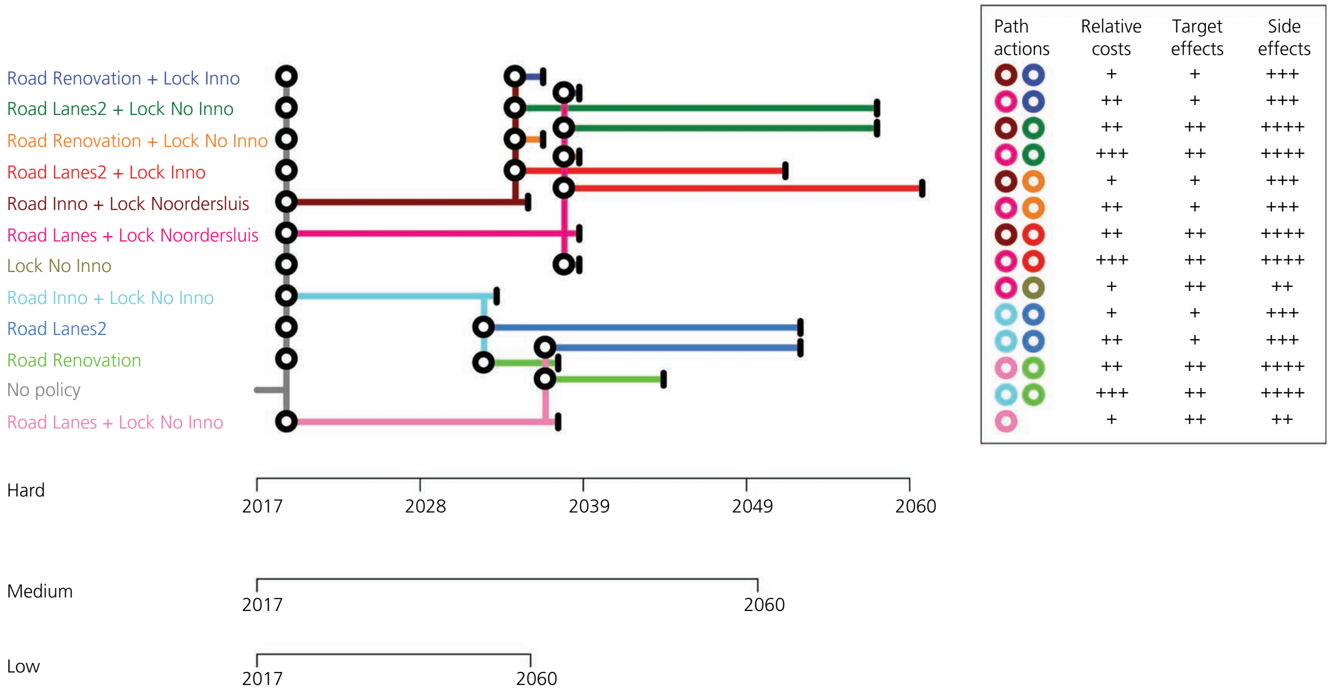
Infrastructures are multidimensional asset systems: they have multiple functions, and they have a technical and functional lifetime. In current asset management practices, interventions have to incorporate the technical and functional lifetime for multiple functions at the same time. This involves the 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, particularly 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 infrastructure's performance.

### Long-term adaptive framework

With the adaptation pathways approach, an adaptive long-term plan can be constructed on the basis of the results of the ESDMA simulations. This plan is built on the basis of a framework which includes interventions to be taken in the short term for both the lock and the road in order to guide actions in the future. Figure 9 presents the map that was developed with the case study's run data for the long-term planning of the lock and road system. The adaptation pathways map is further explained in the figure description. The figure is scaled on the hard scenarios (large climate effects and large population growths). The timescales for the medium and low scenarios are adjusted to this scaling. 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. Therefore, the framework can be adapted to new experiences and insights.

## Conclusion

The objective of this study was to develop a robust set of intervention policies for a set of interconnected infrastructure asset systems. Therefore, the authors analysed the contributions of a multivariate simulation method within the long-term planning of




Q10 Figure 9. Combined adaptation pathways map of intervention policies including scorecard. On the left, the combination of intervention policies for the road and the lock are listed. The intervention policies have a certain lifetime. This lifetime is presented as coloured bars. The lifetime of an intervention policy is reached if the performance of the infrastructure system is below the threshold. For both infrastructure systems, the threshold was based on the critical I/C factor. If the threshold is reached, the policy reaches a so-called tipping point (white circles with black border). At this tipping point, a different intervention policy needs to be chosen. On the right, each combination of intervention policies has certain life cycle costs, target effects and side effects. These aspects are indicated, in the scorecard on the right, with a '+' mark. The following interventions and combined interventions can be found on the left hand side: Lock Noordersluis is a complete renovation of the Noordersluis, extending its lifetime beyond the simulation time. Lock No Inno is construction of a new lock, which is an exact copy of the new sea lock that is currently being constructed at IJmuiden. Lock Inno is construction of a new lock, which applies the latest innovations possible. Road Inn is a complete renovation (variable maintenance intervention) of the Amsterdam Ring A10, with additional innovative measures to extent the technical lifetime. Road Lanes is a complete renovation of the Amsterdam Ring A10 (large intervention); in addition, two lanes (one per direction) are added to the A10. Road Renovation is large renovation project on the whole Amsterdam road network. Road Lanes2 is the addition of two lanes (one per direction) to the whole Amsterdam road network



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large intervention decisions in infrastructure asset management. The analysis was done by applying a 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.

First, the authors assessed the complex nature of the infrastructure systems. Interventions were implemented on the network level for both the road and the lock system to improve the performance of the whole infrastructure network by using the adaptive framework (Figure 9). The effects that these interventions had on the specific asset systems (e.g. harbour, road and lock) and sectors (i.e. population, urbanisation and economy) were measured on the operational level. The KPIs for the individual asset systems were visualised (Figure 3–6).

The authors showed the influence between infrastructure systems with direct interfaces and infrastructure systems that indirectly influenced one another through other systems. The authors interpreted the effects of an intervention dynamically over time with the implementation of subsequent interventions to assure maximum asset performance.

Another assessed aspect of complexity was the multifunctional performance of the infrastructure systems. With the proposed approach, the technical and functional performance of the lock and road system was analysed under a multitude of plausible future scenarios. This was done for both the primary (i.e. transportation) and the secondary (i.e. flood protection and sewer drainage) functions. Interventions for both functions were combined during the same intervention moment, to increase the economic viability of the long-term planning.

Second, the authors 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 functions was measured dynamically over time when subjected to dynamic uncertainty. By gaining insight into 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 dynamic pathways map was created to guide actions in the future. 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 thus be adapted to new experiences and insights.

## Discussion

The authors demonstrated in this study that combining the ESDMA and adaptation pathways approaches has the potential to contribute to the long-term planning of large intervention decisions within infrastructure asset management. The authors, however, also found some limitations of the model, which have to be assessed in future research.

The first limitation is the use of a relatively simple model. The model built in this study relies on some simplicity due to time constraints, limited available information and the required use of fast and simple models in order to be able to construct adaptation pathways. The model can be made more specific, and the scope of its impact can be made more extensive. Second, the ESDMA and adaption pathways approach was applied to a single case. To prove the usability of the approach within the field of infrastructure asset management, more and different cases have to be assessed. Third, the model used within this study required many input values within various different subsystems. The authors acknowledge that even though the model was verified and validated, not all values and results are representative for the case study. Furthermore, some calculations had to be simplified due to time constraints. It is recommended that these calculations be performed more extensively.

## Recommendations

Following the conclusions of this study, the authors formulated the following recommendations for further research and further use in asset management practices.

The authors recommend additional research 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 visualising 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 consequently excludes a wide variety of scenario combinations. Moreover, additional research is recommended on the practical use of the ESDMA and adaptation pathways approach in infrastructure asset management. The combined approach has important contributions to infrastructure asset management. However, practical implementation needs to be assessed. Building a specific model implies large costs and time, whereas a too general model results in less satisfying outcomes.

The future uncertainties described in this study do not include developments in 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 impacts (i.e. technical and functional) for the asset systems. However, political influences can shift a preferred intervention policy, found by the adaptation pathways, to another policy.

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 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.

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