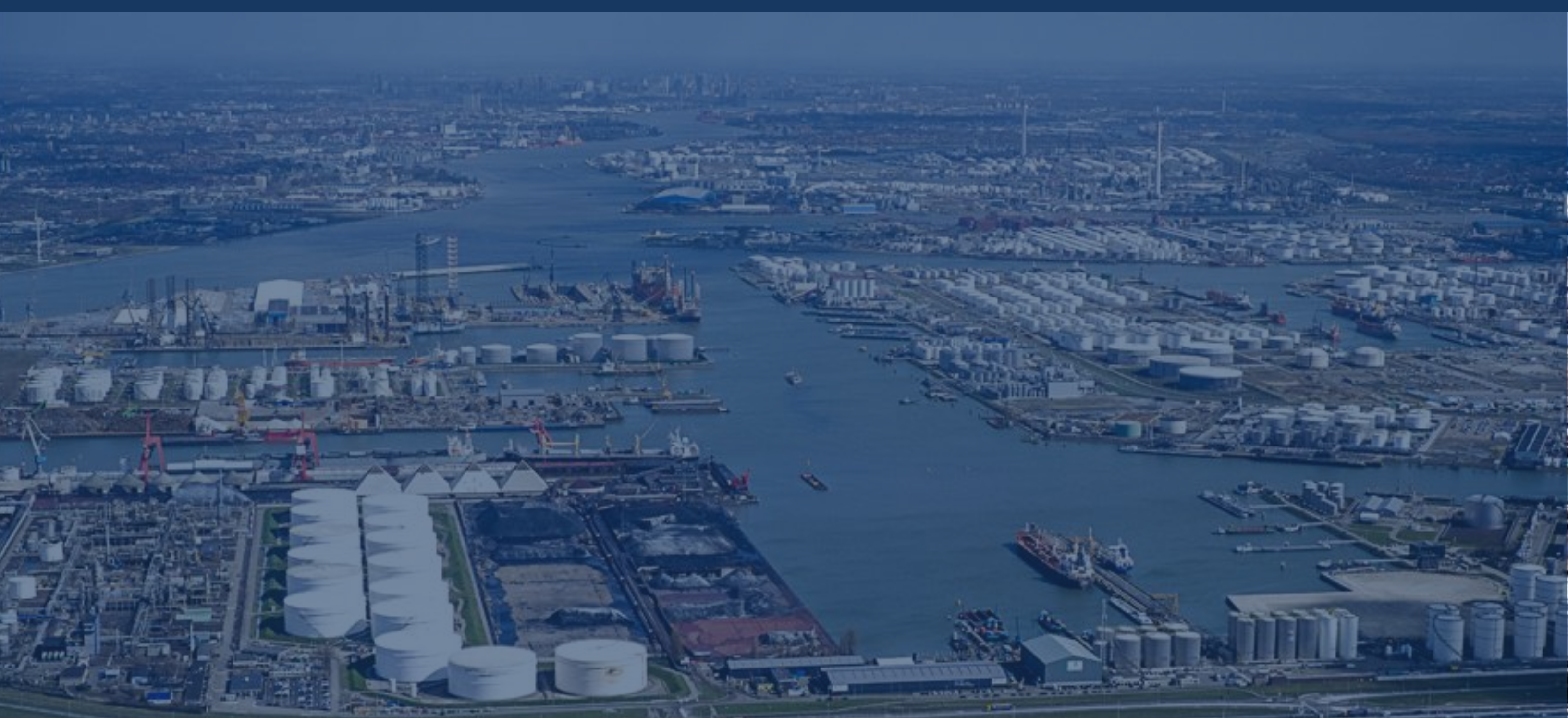
Multi-scale-multi-models: from forecasts to strategy and operations in the Port of Rotterdam

A proof of concept of the design and implementation of a model ecosystem that supports the Port of Rotterdam Authority in their decision-making process



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Colophon

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Preface

'It always seems impossible until it's done.' – Nelson Mandela

This thesis will close my time in Delft, my student time is finished. A time on which I can look back positively, including on my master thesis. It may have been hard sometimes, but I enjoyed most of it.

To start, I would like to express my gratitude to my graduation committee. First, Alexander, who served as Chair of the graduation committee. Thank you for the very valuable feedback during the several meetings we had. Igor, my first supervisor, you always challenged me to think one step further, and to make me get the best out of it. I want to thank you for making me aware of my capabilities, and not to doubt my own knowledge too much. When I started this thesis project, I had zero knowledge about Python (I do not recommend learning a new programming language during your master thesis). Jan, thank you for helping during my endless struggles with Python and EMA. And Eric, thank you for having a smart solution for all the mathematical issues I had. Because most of the committee and I are from the TU Delft, your different points of view have, on occasion, led to interesting results. And also Karin, thank you for letting me roam around the organisation.

I would like to express my gratitude to the Port of Rotterdam Authority, which gave me the chance to not only design a theoretical ecosystem, but to apply it to a real system. It gave me the opportunity to interview people from all different departments, which gave me a real understanding of how it works at the port. It almost goes without saying that I would like to thank all those who I had the pleasure of interviewing, however, I would like to thank some people in particular: Anneke and Jelle. Your input made the difference in my research.

There are also some people to whom I would like to say something a bit more personal. First, Ron and Laurens. Without you two, these last months would not have been the same. We really did this together. Next to our endless bad jokes, our daily meals at the Hangout and our plays with Barricade, you were always there to help me when I got stuck with my thesis (or my article). Maggie, thank you for making my thesis sound really English. And most importantly, I thank my parents, my sister, Constant, Sofie and Gina. All the meals you cooked, my laundry you did, the support you gave me, the questions you answered, my things you read, without all of you, I wouldn't have made it.

Amber Pilar Amalia van Oel,

Delft, 2017

Notes on data used in research

1. Specific information about the Port of Rotterdam Authority is part of the confidential appendix.
2. The transcripts of the interviews with Port of Rotterdam Authority employees are part of the confidential appendix.
3. The data used in the models is not based on the real data of the Port of Rotterdam Authority, fictitious numbers are used.
4. The full software codes can be found on: https://github.com/ambervanoel/Master_thesis.

Summary

The changing world trade due to the economic crisis, the energy transition, digitalisation, consolidations and globalisation are examples of uncertainties impacting the system of the Port of Rotterdam. One of the main stakeholders involved in this unpredictable and uncertain world is the Port of Rotterdam Authority (PoRA). The objective of PoRA is *'to enhance the port of Rotterdam's competitive position as a logistics hub and a world-class industrial complex'* (Port of Rotterdam Authority, 2017a). PoRA is responsible for the port and industrial area of Rotterdam. The uncertain and unpredictable future make it hard for PoRA to make reliable statements about the future, and complicates it to make robust strategic and operational decisions. PoRA developed a decision-making process in which multiple models and tools are used to support them in these decisions. PoRA states that this process, and these tools and models are static, inefficient, error-prone, labour-intensive and most importantly, these scale very poorly.

One way to systematically explore the uncertainties within a system is by using simulation models. These simulation models should represent the dynamics of the system and give the possibility to explore a large variety of possible future scenarios. The system of PoRA is becoming too complex and the environment is too uncertain to capture the entire system in one simulation model. A system of models should be developed. The question that is answered in this research is therefore:

How can a system of models support the Port of Rotterdam Authority in their decision-making process?

The purpose of this research is to discover in what way a system of models could support PoRA in their decision-making process and to demonstrate the usefulness of such a system of models. It would not make sense to develop a 'real' system of models before the usefulness is determined. To investigate the added value of a system of models and to demonstrate the usefulness, a proof of concept will be designed and implemented. This proof of concept allows one to explore in what way such a system can support PoRA, despite the absence of a real system of models.

The system of model is approached as a model ecosystem. A model ecosystem is a multi-model system in which multiple models interact with one other. In this approach, the focus is not only on technical characteristics of the system, but also the social elements are incorporated, thus the focus is on the socio-technical system.

The design of the model ecosystem is based on the current decision-making process of PoRA. The first step in the design of the model ecosystem is the system analysis. Several interviews with experts from various departments are conducted. Through these interviews an overview of the current decision-making process is obtained and the main challenges are ascertained. The process overview is shown in Figure 1.

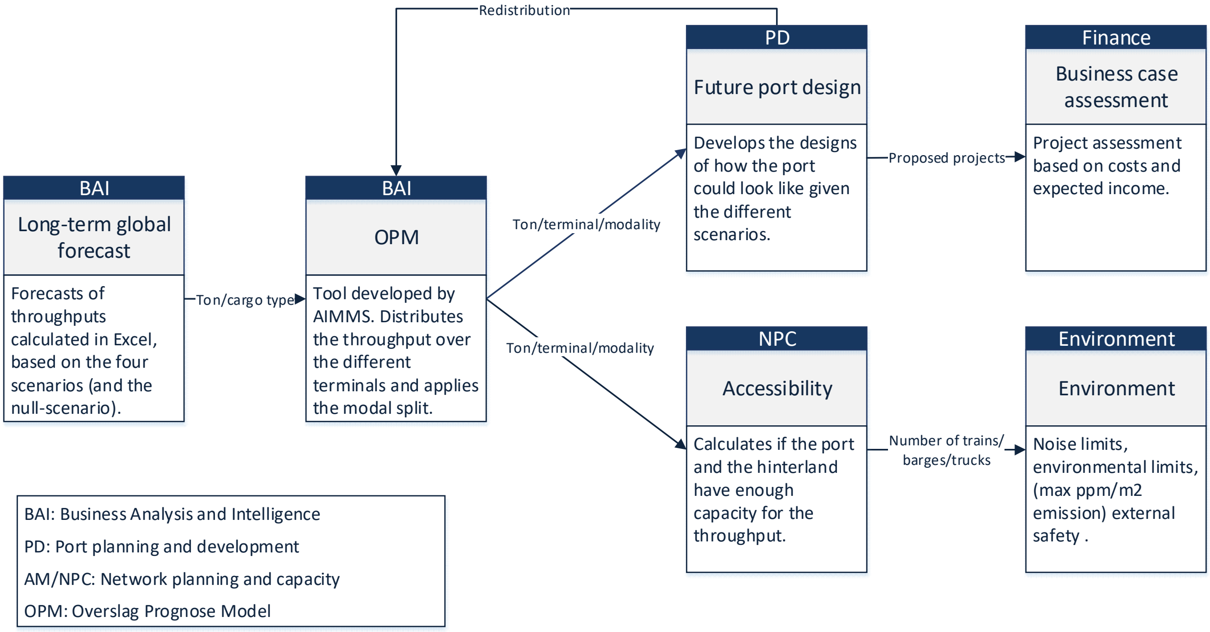

Figure 1: Overview of decision-making process PoRA

The main process elements in the decision-making process of PoRA are:

- development of long-term global forecasts
- development of port designs
- perform environmental checks
- assess infrastructural capacity.

The most important challenges encountered within this decision-process are (i) the lack of connection between models of the different departments, (ii) the use of Excel, which is error-prone, labour-intensive and time-consuming and (iii) the fact that only five (or sometimes only one) scenarios are used in the assessment of new projects and port designs.

Based on the system analysis, the requirements and specifications for the model ecosystem are defined. The functional requirements of the model ecosystem are:

- demonstrate possible futures
- calculate business cases
- estimate the business value of PoRA
- determine the division of throughput over different terminals
- define the environmental impact of changes within the port area
- define the infrastructural impact of changes within the port area;
- determine safety areas, bottlenecks and opportunities
- translate global forecasts to forecasts for Rotterdam.

The system specifications of the model ecosystem are:

- central place for models of model ecosystem and data
- automated tools
- coupled models
- explorative focus of model ecosystem
- modularity
- use of simple models
- strict defintion of input and output of the components.

These requirements and specifications lead to the design of the model ecosystem shown in Figure 2. The design of the model ecosystem consist of five components, which all relate to one or more functional requirements (elements within the decision-making process).

The most important characteristics of this design are the modularity, the use of automated tools, the coupling between the various components and the strict definition of input and output of the components. Because the design consists of a modular system, in which the different component can be adjusted or replaced, it allows PoRA to improve, adjust or expand the existing models by consulting the experts who have most knowledge about these components. Because the components within the model ecosystem are coupled, PoRA is able to explore the entire chain within the decision-making process. Due to this coupling and due to the use of automated tools, PoRA can explore and assess what impact particular changes in one of the components have on the rest of the system.

A proof of concept of this design is developed. For this, the design is applied to the coal case. The coal market is one of the markets in which the uncertainties are very large and the impact is enormous. The proof of concept consists of various simple and small simulation models. These models are coupled to develop one ecosystem of models. This coupling is executed by using a master-component. This master-component manages the communication and interaction between the different components of the model ecosystem.

Besides the practical challenges, PoRA also struggles with making robust decision, because the decisions are made under deep uncertainty. By applying Exploratory Modelling and Analysis (EMA) to the model ecosystem, new capabilities become available to explore the uncertainties that PoRA is facing. The model ecosystem in combination with EMA enables PoRA to analyse the entire set of plausible futures and to explore the uncertainties in a systematic way. By using scenario discovery, PoRA is also able to develop narratives that describe the various uncertainty subspaces in which different types of future paths are grouped. It gives insights in the uncertainty subspaces that lead to particular (desirable or undesirable) outcomes. These subspaces can be translated to *communicable, internally consistent, and plausible narratives.*

Four main types of future paths are defined:

1. monotonically increasing
2. monotonically decreasing
3. non-monotone, starting with a decrease
4. non-monotone, starting with an increase.

When the path is monotone, the path either increases or decreases over time. When the path is non-monotone, the path changes direction during the coming 40 years.

Through this way of using models, the focus shifts from focusing on the right data and developing as detailed models as possible, to focusing on what types of futures may occur and in what way PoRA can adjust their strategy to meet their objectives.

Based on the above the main research question can be answered:

How can a system of models support the Port of Rotterdam Authority in their decision-making process?

With a model ecosystem, PoRA is armed with a set of tools to address the challenges encountered in their decision-making process – both the practical challenges and the challenges regarding the deep uncertainty. It eases the decision-making process, because the system is approached in a more integrated manner and most of the practical issues are solved (e.g. use of Excel, inconsistency, inefficient loops etc.). In addition, with the model ecosystem in combination with EMA, new capabilities become available to explore uncertainties. It enables PoRA to approach the uncertainties in a systematic way. The decision itself may not always change, but the process of making this decisions will be different. Decisions will be better substantiated, deliberated, and informed by a model ecosystem. This makes it easier to justify particular decisions. The model ecosystem dams the future and can reduce the uncertainty space. By reducing this uncertainty space, a model ecosystem enables PoRA to make no-regret decisions, which makes them more resilient.

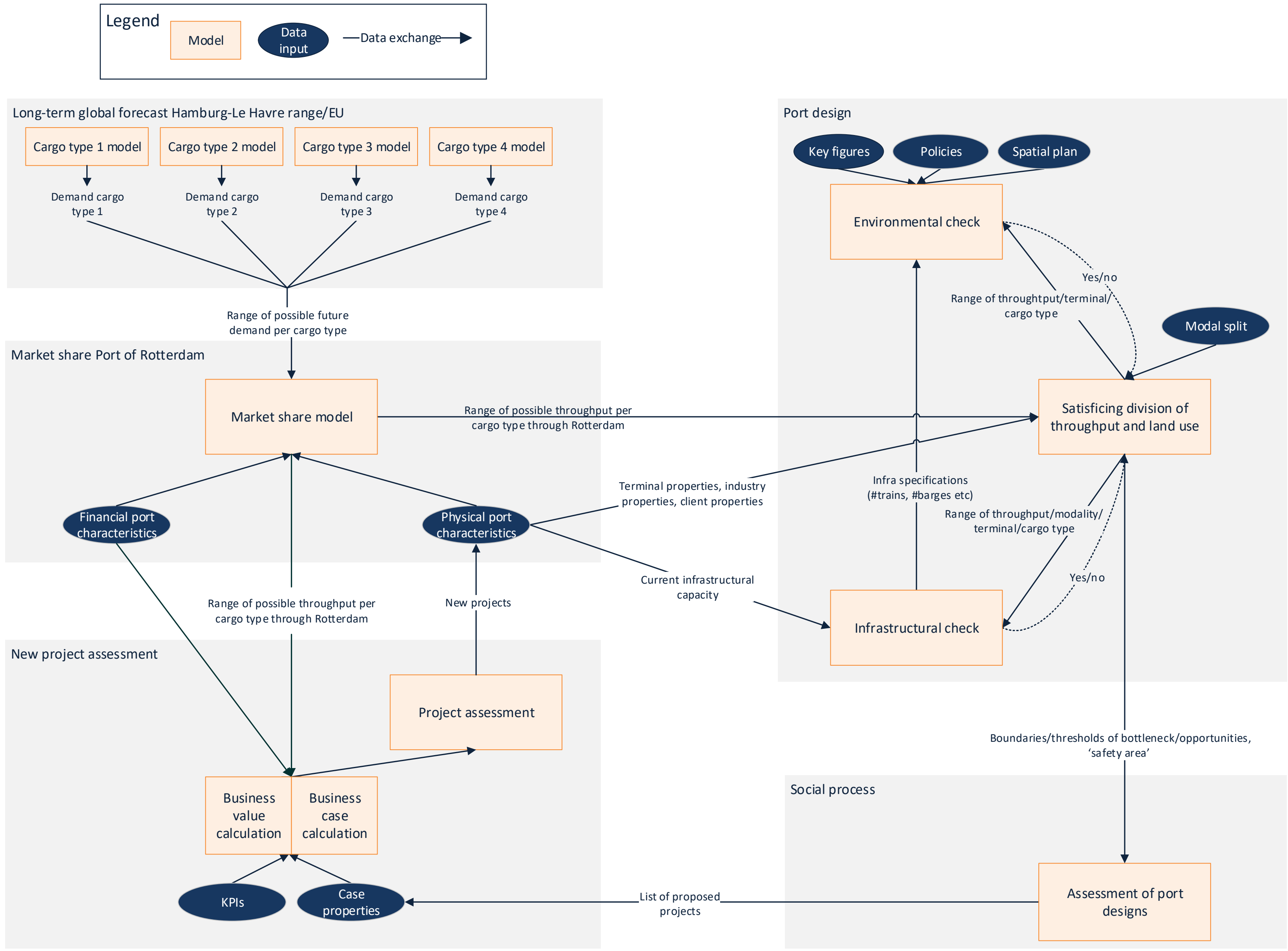

Figure 2: Design of the model ecosystem

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List of abbreviations

ABM	Agent-Based Modelling
AM/NP	Network planning and capacity
BAI	Business Analysis and Information
CBL	Containers, Breakbulk & Logistic
CS	Corporate Strategy
EMA	Exploratory Modelling and Analysis
HLH range	Hamburg-Le Havre range
HOC	Haven Ontwikkelings Cyclus
PD	Port development
PIM	Process Industry & Bulk
PoR	Port of Rotterdam
PoRA	Port of Rotterdam Authority
TP	Throughput

1

Introduction

“"For the moment, the government is not planning to close extra coal plants in the Netherlands. The Lower House had asked for it, but the government does not want to make any decisions now and wants to leave it to his successors” (NOS, 2017)

What will happen when the formation of the Dutch Parliament is finished? Will they decide to close the coal plants in The Netherlands? And if they do, what impact will this have on the Port of Rotterdam? Whether or not the coal plants will be closed and what the effect will be on the Port of Rotterdam (port area) is one of the innumerable uncertainties where the port area is subjected to. The changing world trade due to the economic crisis, the energy transition, digitalisation, consolidations and globalisation are other examples of uncertainties impacting the port area (Port of Rotterdam Authority, 2016b).

One of the main stakeholders involved in this unpredictable and uncertain world is the Port of Rotterdam Authority (PoRA). The objective of PoRA is *‘to enhance the port of Rotterdam’s competitive position as a logistics hub and a world-class industrial complex’* (Port of Rotterdam Authority, 2017a). PoRA is responsible for the port and industrial area of Rotterdam. There main tasks are the sustainable development, management and operation of the port. And maintaining the safe and smooth handling of all shipping. They invest in new and existing infrastructure and manage to obtain the right mix of business within this area. In order to do so PoRA makes strategic considerations for the long-term vision and chooses strategic paths. They translate these strategic considerations to operational decisions like the allocation of required capacity for land use, infrastructure and environmental space and operational port planning.

The system of PoRA is a heterogeneous system that consists of multiple varying, physical and social, components and processes. Which are interconnected and interrelated and in which a high degree of unpredictability and uncertainty exists. These characteristics of the system make it hard for PoRA to make reliable statements about possible futures and it complicates it for PoRA to make robust and resilience[1] strategic and operational decisions resistant to this increasingly uncertain and unpredictable future.

1.1 Research context

The problem explored in this research consists of two parts. The first part is related to the practical issues PoRA is facing. The second part concerns the scientific and technical issues raised by these practical issues of PoRA. The problem exploration for the first part is performed by investigating the system of PoRA. This exploration is based on literature and interviews with PoRA employees. The problem exploration for the scientific and technical part is executed by performing a literature research in state of the art literature.

1.1.1 Practical problem Port of Rotterdam Authority

As mentioned in the previous paragraph the system of which PoRA is part, consists of a large amount of differently characterised components, some examples:

- global markets of different cargo types
- large transportation infrastructures
- traffic
- capital intensive power plants
- business cases of new projects
- port choices of companies
- consolidation and alliance formation in the container market
- land use and land issue
- distribution of throughput over terminals.

These components differ in multiple aspects and scales. They differ in geographical scale: some concern only local aspects while others concern more global aspects. They differ in type: some components are physical infrastructures while others concern the social process within a particular market. And where some components have a short-term time frame, others have a long-term time frame. The decisions made by PoRA itself are also differently characterised. From strategic to operational and from long-term to short-term decision. The issues on which decisions are made vary strongly too, from physical infrastructure performance to environmental impacts. These decisions are often characterised by their large size, great impact, high costs, complexity and long duration (Hallegatte, Shah, Lempert, Brown, & Gill, 2012; Taneja, Ligteringen, & Walker, 2011). And because the world is getting more and more complex, the process of making these decisions is also more complex. Also the variety of stakeholders involved makes the decision-making process more complex (van Geels & Klijn, 2017). This large variety of characteristics of components and decisions

[1] *"The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions"* - (Lounis & Mcallister, 2016)

have great impact on the decision-making process of PoRA and complicates their decision-making process.

A second aspect that complicates the decision-making process of PoRA is the fact that they are facing a lot of uncertainties regarding the future and that many actors are involved within the process of dealing with these uncertainties regarding the decision-making process. All of these actors have a personal point of view regarding these uncertainties and regarding the decision-making process and decisions are made under deep uncertainty (Kwakkel, Auping, & Pruyt, 2013).

PoRA is developing and implementing various models and tools as a first step to overcome the earlier mentioned challenges in their decision-making process. These tools support PoRA in their decision-making process by obtaining more insights in possible futures and enable more quantitative substantiation to their decisions. However, most of these models and tools are made in Excel and need to be operated and adjusted manually (further elaborated in Chapter 3). PoRA states that these processes are static, inefficient, error prone, labour-intensive and most importantly, scale very poorly (source: interviews). Furthermore, these models and tools are developed separately at different departments and most of them are not coupled or integrated. It limits the ability to consistently explore investment business cases and opportunities throughout the entire chain and across many scenarios.

1.1.2 Scientific and technical issues

In literature many articles are found concerning the use of coupled models to support decision-making under deep uncertainty in a complex system. However, there is not a clear framework that can be applied to the issues of PoRA. Authors do agree upon the complexity of developing models in such a system. In this paragraph an overview is given of the most relevant issues for PoRA mentioned by several authors.

Multi-scale The multi-scale element present in the different components is an important factor that complicates the use of multiple models for one system (Borgdorff et al., 2012; Cappuccio, Tieri, & Castiglione, 2015). It is mentioned that the coupling between two models at a different scale is difficult because a translation needs to be made from one scale to another and the factors within a system are scale-dependent (Veldkamp et al., 2001).

Uncertainty Different dimensions of uncertainties exist, besides the fact that the system of the port area is subject to many uncertainties, modelling a complex system involves an additional level of uncertainty (Walker et al., 2003). An example hereof is the model structure uncertainty: the choice for a particular model can be seen as an extra uncertainty; the parameters included in a model, relations within a model etc. (Kwakkel, Walker, & Marchau, 2010).

Formalism[2] When multiple models are developed separately, the chance exists that the models are developed with a distinctive formalism. Because not all formalisms can communicate directly, this aspect complicates the coupling of multiple models. For example, PoRA developed a tool in AIMMS (software tool), which cannot be directly coupled to their Port Optimizer (a different software tool).

Use of existing models When building an individual model, developers will not have in mind that the models will be coupled later in time. This means that an often named approach in literature, the top-down approach, is more complicated to apply when models already exist. Top-down is a design method that begins with the determination of general principles and ends with the details.

1.1.3 Research objective

This research will be done to strengthen the use and development of models within PoRA and provide context for strategic and operational decisions. This will be done by designing a system of models to treat uncertainties in a more systematic and quantitative way to support the decision-making process of PoRA. The coupled models will be used to support PoRA in managing the interaction with the large variety of stakeholders more systematically and to oversee the socio-technical consequences of the long-term global scenarios on the strategic and operational decisions. The objective of the research is to show that particular modelling and coupling concepts are working. Making more complex models means more variables, more uncertainties and more computation time, but the principle remains the same. The deliverable of the research is a proof of concept of a model ecosystem.

> *'A proof of concept is a demonstration, the purpose of which is to verify that certain concepts or theories have the potential for real-world application. A proof of concept is therefore a prototype that is designed to determine feasibility, but does not represent deliverables.'* (Techopedia, 2017)

This proof of concept will be developed by applying the design to a case of PoRA and develop a system of models with multiple simple and small models. The focus of the research will therefore not be on the details of different modelling techniques, but on the coupling of various models within the system of models.

1.1.4 Scientific relevance

The research will contribute to the existing literature by giving more insight into the possible techniques for coupling multi-scale models. It will give researchers the opportunity to explore the interdependencies and mutual influences of multi-scale problem fields. It enables the possibility to couple models developed by different stakeholders with a different point of view.

[2] Models are developed following a particular set of rules and principles: the model formalism

1.1.5 Societal relevance

Even though this research is focused on PoRA, the knowledge about these coupling methods can be applied to all multi-scale complex systems. The research will not only be useful for PoRA, but it will also create benefits for the broader urban context in which the port is operating and for other, similar, organisations like PoRA.

1.2 Research questions

The main research question that will be answered in this research is as follows:

How can a system of models support the Port of Rotterdam Authority in their decision-making process?

1. How is the current decision-making process of the Port of Rotterdam Authority organised and what are the challenges encountered in this process?
2. In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process?

The purpose of this research is to discover in what way a system of models could support PoRA in their decision-making process and to demonstrate the usefulness of such a system of models. It would not make sense to develop a 'real' system of models before the usefulness is determined. To investigate the added value of a system of models and to demonstrate the usefulness, a proof of concept will be designed and implemented. This proof of concept enables the answering of this second question, despite the absence of a real system of models.

3. How would the implementation of a system of models impact the Port of Rotterdam Authority?

1.3 Scope

The previous paragraphs speak of ‘a decision-making’ process within PoRA. One can imagine that within PoRA thousands of different kinds of decisions are made every day. In this paragraph a short description will be given of the decision-making process that will be treated in this research.

PoRA is the landlord of the ‘Port Industrial Complex’. As mentioned before, their mission is to create an attractive business climate in order to attract new customers and obtain a large market share. In order to reach these objectives PoRA takes both strategic and operational decisions. The strategic and operational decisions made, consider the strategic paths they have to take, which cargo type they should focus on, which type of new customers they should attract, the investments in existing or new infrastructure, the release of land or the introduction of commercial actions like port due discounts. PoRA developed a decision-making process to support these strategic and operational decisions.

Every ten years PoRA adjusts their Port Vision. Within this vision it is stated which direction PoRA is going and which aspects they will focus on. In order to bring the port area from the current situation to the desired situation a strategy is developed. This strategy consists of a corporate strategy, a commercial strategy and a financial strategy. These strategies are released every five year. This strategy is influenced by the long-term global scenarios and corresponding forecasts developed by PoRA. When particular changes and new trends influencing the port area are ascertained, the strategy will be adjusted in such a way that it contributes to the path leading to the Port Vision. In order to follow this strategy in the right way, a yearly update is made after which it will be determined how to best design the future port industrial complex so it fits within the space of the port area. This future port design will then be tested, and if needed, adjusted for accessibility and environmental use. The result is a desirable port design for 2040 that fits within the available user space. This annual process is called the 'Haven ontwikkelingscyclus'. An overview of this decision-making process over time is shown in Figure 3.

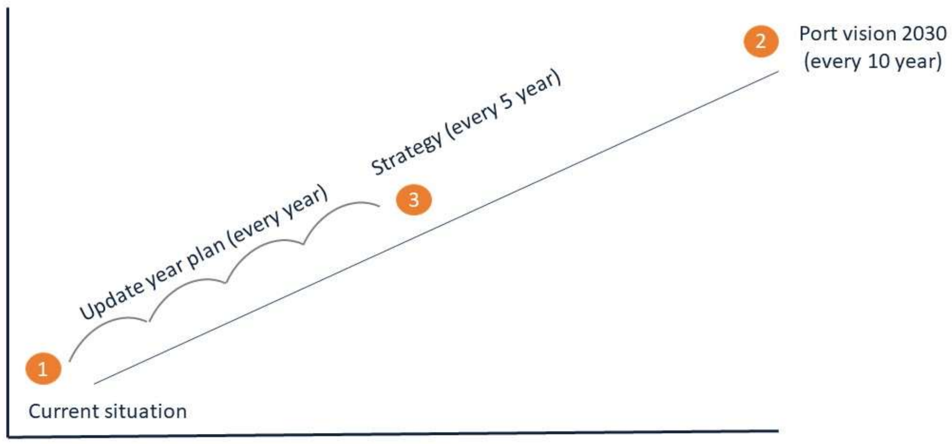


Figure 3: Decision-making process of PoRA over time

Coal

The throughput of the Port area is divided in 12 cargo types divided over three categories. In Table 1 an overview of the different goods per category is shown.

Table 1: Cargo types

Liquid bulk	Dry bulk	Breakbulk
Crude oil	Agribulk	Container
Mineral oil	Ore	RoRo
LNG	Coal	Other breakbulk
Other liquid bulk	Dry biomass	
	Other agribulk	

These cargo types all have different characteristics, therefore, it is not possible to develop a proof of concept of a system of models that fits all 12 cargo types. It is thus chosen to develop a proof of concept for one cargo type: coal.

The coal market is one of the markets in which the uncertainties are very large and the impact is enormous. As mentioned in the first paragraph, a lot of uncertainty exists around the closure of coal plants. A second large uncertainty is the course of the energy transition. Some say the downfall of fossil energy approaches (Duursma & Postma, 2017), however, figures about the throughput to the port area do not lie: throughput of coal is increasing in 2017 (Postma, 2017) (Port of Rotterdam Authority, 2017b). These contradictory statements about coal make this cargo type eminently interesting to dive into. Coal is divided in two sub types: cokes coal and steam coal. Cokes coals are the coals that are used for the production of iron. Steam coals are the coals that are used for energy production. These two flows of coal are rather independent from each other and can be analysed distinctively. It is therefore chosen to only include steam coals in the scope of this project.

1.4 Structure of the report

The report consists of four parts: the system analysis, the design of a system of models, the development of a proof of concept and the analysis of the results. In the first part the current process, the use of models in the current process and the challenges encountered in this process will be analysed. The results of the system analysis will be used as input for the second part of the research, the design of a system of models. Based on the system analysis the requirements and specifications of the system will be defined, after which the specifications will be used to design a system of models. In the third part this design will be applied to the coal case of PoRA, resulting in a proof of concept. Based on the design and the proof of concept, in the last part, it will be assessed in what way a system of models could support PoRA in their decision-making process and what the implications are for PoRA of implementing such a system. The report concludes with the discussion, conclusion and a reflection.

2

Methodology

In Chapter 1, the problem of PoRA is explored, the research questions are formulated and the objective of the research is defined. In this chapter it is explained how this job is done. First it is discussed that the problem within this research is approached as a socio-technical problem. Which means that not only the technical aspects are taken into account, but where the social aspects play an important role too. After that it is explained that the system of models that is developed is approached as a 'model ecosystem', in which multiple models interact with one another. In the third paragraph the research design with its corresponding research steps, methods and techniques is introduced. It is demonstrated how, and with what methods and tools, the research questions are answered.

2.1 Research approach

In this research not only the technical modelling and model coupling aspects needs to be taken into account. Also the large variety of stakeholders, expert knowledge and the social aspects of the decision-making process within PoRA are of great importance. In this research the system of PoRA that will be analysed is, therefore, approached as a socio-technical system. In a socio-technical system approach both technical and social aspects of the system need to be integrated.

"The rationale for adopting socio-technical approaches to systems design is that failure to do so can increase the risks that systems will not make their expected contribution to the goals of the organisation" (Baxter & Sommerville, 2011, p. 4).

That is to say, when fancy advanced models are developed for PoRA, but the implementation of these models within the organisation is lacking, the value of these models is limited.

2.2 System approach

One way to systematically explore the uncertainties within a system is by using simulation models (Fujimoto, 2017). These simulation models should represent the dynamics of the system and give the possibility to explore a large variety of possible future scenarios. As mentioned in Chapter 1 the system of PoRA consists of a large number of varying, physical and social, components and processes. Taken all these different components and processes into account this system in its entirety becomes too complex and the environment is too uncertain to capture the entire system in one simulation model (Yilmaz, Lim, Bowen, & Ören, 2007). A concept often named in literature as a solution for these type of problems is the development of a multi-model system.

'A multimodel is a modular model that subsumes multiple submodels that together constitute the behaviour of a complex multi-phased process.' (Yilmaz et al., 2007, p.825)

The system of models that needs to be designed should be approached as a Complex Adaptive System. The whole is more than the sum of its elements and therefore needs to be approached as a whole (KH van Dam, Nikolic, & Lukszo, 2012). A change in one part of the system will affect the operation and output of other parts and the operation and output of the system as a whole. A clear definition of a complex adaptive system is given by Nikolic (2009):

"An adaptive complex system is an open system made up of numerous components that interact with one another in a nonlinear way and constitute a single, organized and dynamic entity, able to evolve and adapt to the environment." (p. 29)

Approaching the system of models as a multi-model ecology fits this approach very well. A multi-model ecology (or model ecosystem) is a multi-model system in which multiple models interact with one other (Bollinger, Nikolic, Davis, & Dijkema, 2015). In this approach the focus is not only on technical characteristics of the system, but also the social elements are incorporated, thus the focus is on the socio-technical system. The various components should be viewed from a different perspective and treated from distinctive simulation disciplines.

"Viewed through the lens of multi-model ecologies, models are not isolated elements in a vacuum, but potentially sociable individuals coevolving with one another in a changing environment." - (Bollinger et al., 2015, p. 254)

These theories will be used to decompose the system in a systematic way using various techniques discussed in the following paragraphs. Within this theory an integrated approach of modelling will be applied. This integrated approach uses existing models and new models together and the different components of the model ecosystem can be adjusted and improved independently (Bollinger et al., 2015).

We view models as components within this system—competing, coexisting, and coevolving with one another and ultimately contributing to the development of the system as a whole - (Bollinger et al., 2015, p. 253)

The model ecosystem that will be designed consists of three levels:

Level 1: A high-level design consisting of the general objective of the system and the function and purpose of the system components.

Level 2: The logical design, understanding of needs and the conceptual design of the different components. This logical design consist of the individual objectives and characteristics of the components, together forming a coherent ecosystem of interacting tools, contributing to the general objective of the model ecosystem.

Level 3: The detailed design of the application of the model ecosystem on the coal case: the internal elements, relations and functioning, resulting in the specifications of the designs of the individual components.

2.3 Research design

The development of a model ecosystem consists of several steps. The development steps are based on the Life-Cycle Phases of Systems Engineering of Sage & Armstrong (2000). The research design is shown in Figure 4.

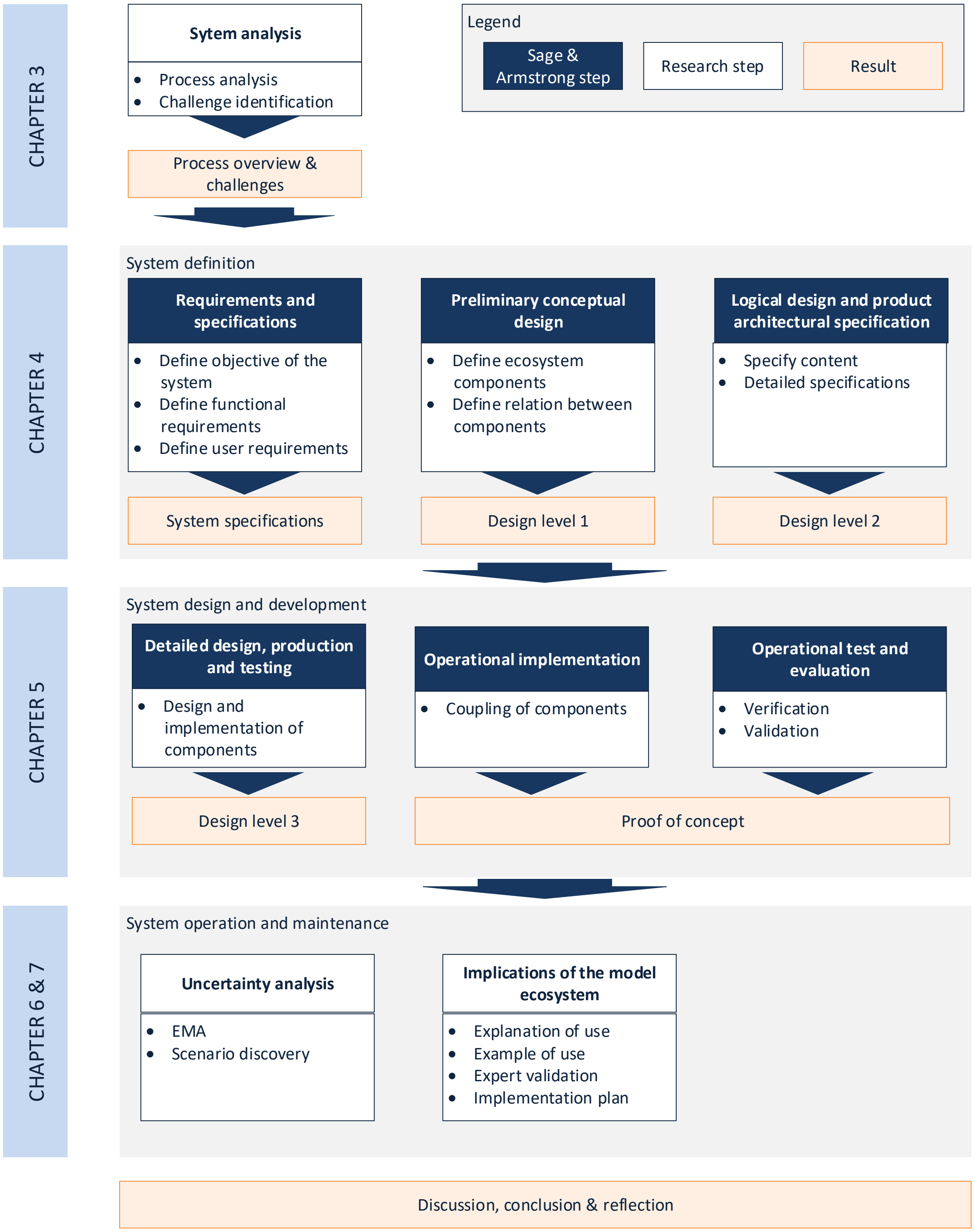


Figure 4: Research design

2.3.1 Methods and techniques

As explained in the previous paragraph, several methods and techniques need to be applied in order to answer the main research question. The most important methods and techniques are explained.

Interviews with experts Interviews are conducted in order to analyse the current decision-making process of PoRA. It is chosen to hold one-to-one, semi-structured interviews. This method ensures that the main topics area treated, but allows one to go deeper on particular subjects and, therefore, obtain more detailed information about the process (Boyce, 2006). Together with the PoRA external supervisor a main list of departments is made of which a respondent should be interviewed:

- Business Analysis and Intelligence (BAI): is a staff department of the commercial departments Containers, Breakbulk & Logistic (CBL) and Process Industry & Bulk (PIM). The department performs various tasks and projects that support and feed the primary activities of these teams
- Port planning and development (PD): responsible for making the Master plans[3].
- Network planning and capacity (AM/NPC): keeping the port accessible for all modalities, for both the port area itself and to the hinterland corridors.
- Environment: responsible for indicating the environmental use area within a theme and assess new port designs whether they fit within the environmental limits.
- Finance: responsible for the future oriented financial affairs, the strategic finance, concerning long-term visions, investment projects and investment decisions.
- Corporate strategy: responsible for identifying relevant trends and developments that impact the port and translate these into a strategy.

At the beginning of the research the first main interviews are conducted. These interviews are used to analyse the current decision-making process. At the final phase of the research, a second round of main interviews is held. In this round of interviews, the expert validation of the design and the proof of concept is performed. Besides the main interviews, several additional interviews are conducted. These additional interviews had a more explorative character and the information gathered in these interviews is used to obtain a better understanding of the overall organisation, processes and relation between different departments. The complete list of respondents and the full interview questions can be found in Appendix A[4].

Exploratory Modelling and Analysis One way to explore the different levels of uncertainty and future scenarios using a model ecosystem is Exploratory Modelling and Analysis (EMA) (Bankes, 1993). In the current method used by PoRA, only the extreme parts of the scenario axis are used. With EMA it becomes possible to generate insights into the system over the entire space of

[3] The Masterplan is a tool for the spatial control of the desired development of the port for a period up to 2040. The ambitions of the Port Vision 2030, the commercial strategy and business strategy 2016-2020 are the basis for this document. The outcome of the translation of long-term global scenarios and forecasts to strategic and operational decisions is captured within this Masterplan and contains visuals and strategic actions.

[4] The interviews are conducted in Dutch, because the main language used within PoRA is Dutch.

uncertain factors (Greeven, Kraan, Chappin, & Kwakkel, 2016). Even though it is not possible to predict the exact future, a model ecosystem gives enough knowledge about the environment and possible futures to support the decision-making process. This is exactly the strength of EMA, using the available knowledge to support the decision-making process in becoming more robust (Bankes, Walker, & Kwakkel, 2013).

2.3.2 Software tools

In order to develop a proof of concept, the design will be implemented using different software tools. An overview of the most relevant tools is given.

Python Python is a high-level programming language that has several advantages. Python is is open-source and, thus, free and available for all users (Python, 2017). The language is considered easy and understandable. And several coupling packages exist for the coupling of Python models to other simulation tools. Jupyter Notebook will be used as the interface for the development of system elements in Python.

R R is a software tool that can be used for statistical calculations and the construction and displaying of graphics. The advantage of R is that it is also an open-source software. Multiple couplings with other software tools are available in the R library.

Netlogo Netlogo is a simulation tool in which multi-agent models can be developed. The main advantage of Netlogo is that it is also an open-source software (Netlogo, 2017). Again the coupling extensions play an important role in the choice for Netlogo. Both for the coupling with Python and R: an extension exists within the extension packages of Netlogo.

Excel Even though Excel is not suitable for the implementation of dynamic simulation models, it is a tool that is easy in use and controlled by a lot of employees of PoRA. Some small elements of the model ecosystem may be developed in Excel.

EMA workbench The EMA workbench is a set of tools and methods, implemented in Python, that gives the possibility to perform EMA analysis on different types of simulation models. The EMA workbench can be applied to both Python and Netlogo simulation models (Kwakkel, 2017)

3

System analysis

The sub-question addressed in this chapter is: *How is the current decision-making process of the Port of Rotterdam Authority organised and what are the challenges encountered in this process?* The goal of this chapter is, therefore, to provide insights in the current decision-making process. These insights are based on interviews with experts from the different departments. In the first paragraph the current decision-making process is described. An overview of various elements within this process is given and the different departments and their role within the process is explained. In order to discover the challenges PoRA is facing within this process, in the second paragraph, the different elements of the decision-making process are explained in more detail. For every process element the challenges are defined.

3.1 Process overview and role of the departments

In this paragraph the current decision-making process of PoRA is explained. A schematic overview of this process is shown in Figure 5. In this figure each process element is indicated with a number. The process is explained using these numbers.

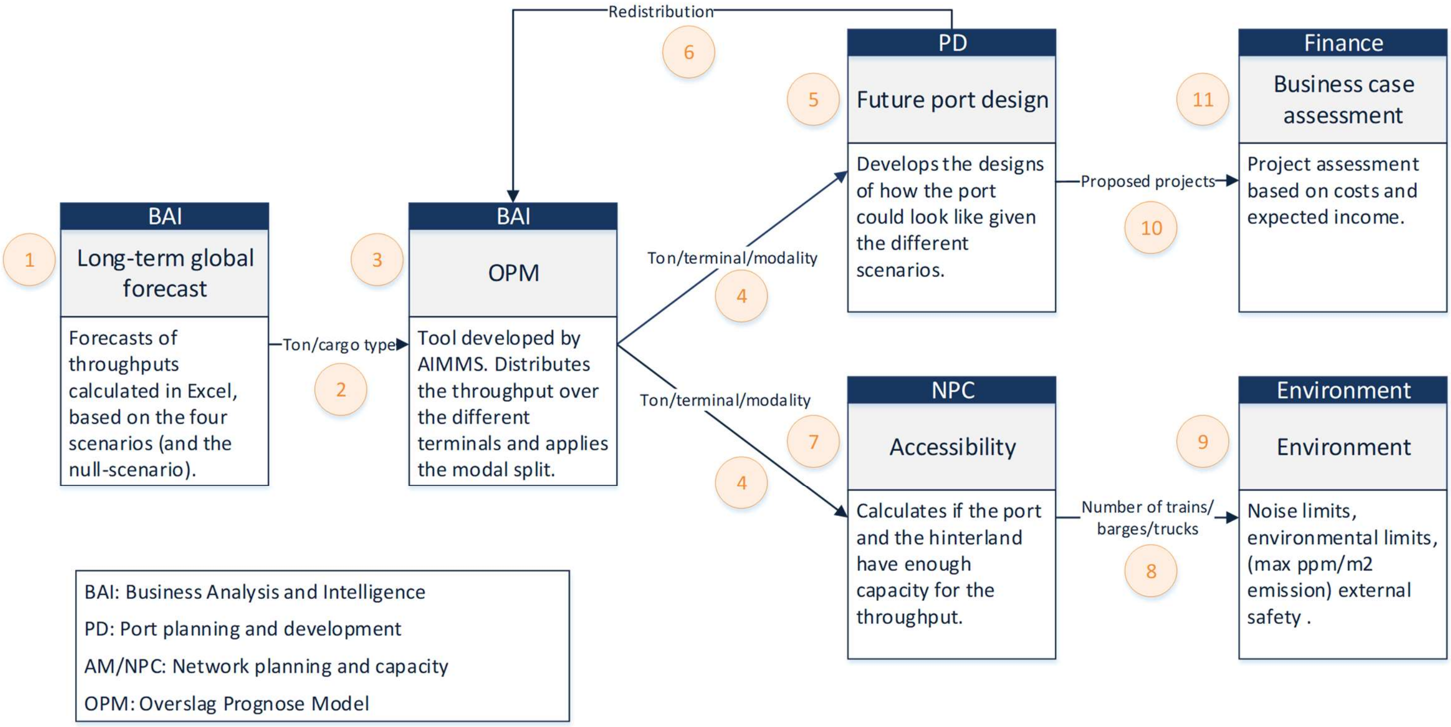


Figure 5: Overview of decision-making process PoRA

<u>1. Long-term global forecasts</u>

PoRA developed five qualitative long-term scenarios for the port area (a brief explanation of these scenarios can be found in Appendix B). In these scenarios, possibilities are sketched of how the port area could change the next 30 years. There are two main objectives for the development of these scenarios. The first reason is to communicate to internal and external stakeholders of PoRA. Scenarios are an appropriate way to communicate the uncertainties of the future system PoRA is facing (Greeven et al., 2016). The second reason for developing scenarios is to quantitatively support strategic and operational decisions. The currently used method for the development of long-term global scenarios within PoRA is scenario based, intuitive logics (also called scenario axis) (Bryant & Lempert, 2009). The uncertainties taken into account and the narrative of these scenarios are chosen and developed by experts. This stakeholder expertise based scenario development is known as the traditional method for scenario development (Herman et al., 2015).

2. Quantitative forecasts

In order to use these qualitative scenarios, they are translated to quantitative scenarios which lead to possible throughputs per scenario, per cargo type for the port area: the long-term forecasts. The calculation of total throughputs for the port area is currently done using qualitative expert input collected in spreadsheets resulting in a long-term global forecast model.

3. Overslag Prognose Model

To use these calculated throughputs for the strategic and operational decisions, the global throughput volumes to the port area need to be translated to more specific divisions of throughputs over the different terminals. The translation of this long-term global forecast model to a more specific throughput division is done in the 'overslag prognose model' (OPM), a tool build in AIMMS. The OPM tool gives an expected distribution of the maritime[5] throughput over the different terminals. This is done based on the historical data of throughput, adjusted by the growth rate coming from the long-term scenarios. The OPM also applies the modal split, which is the division of throughput over the different modalities. This is based on the data from the previous year.

4. Output OPM

The output of the OPM is the expected throughput per cargo type, per terminal and the corresponding division of modalities. The output of the OPM is sent to the PD and AM/NPC department.

5. Port design

The PD department uses these figures to develop possible future port designs.

6. Redistribution

If the division of throughput (outcome of the OPM) does not fit within the port designs, this will be referred back to BAI. BAI on their turn redistributes the throughput and sends it back to PD.

7. Accessibility

The AM/NPC department will check if these designs fit within the currently existing modalities and infrastructure. In order to do so, they translate the volume per cargo type per modality to number of trains, barges and trucks. Because not every barge or train has the same load, they use the 'call size' to calculate this. For every modality a single model exists to estimate the feasibility of the forecasted throughput within the existing infrastructure.

8. Output infrastructure

The AM/NPC department on their turn sends the outcome of their models to the environment department.

[5] Transhipment of goods coming by sea by maritime ship

9. Environment
The purpose of this department is to optimally use and manage the available scarce environment utilization space for the port area. It will be tested whether the proposed developments fit into the zoning plan and the design will be tested for the most imminent environmental aspects external security, noise and air (especially nitrogen deposition).

10. Proposed projects
Based on the future port designs; bottlenecks and opportunities are ascertained, which on their turn lead to new projects.

11. Business case assessment of new projects
New projects are evaluated based on the expected costs and the expected income and their impact on other KPIs. The costs consist of two elements: investments (transportation infrastructure, quays, berths etc.) and operational cost, and the costs of alternative land use. The incomes consist of the income of expected port dues, land renting, and 'opslag'[6]. Projects are rarely rejected on their business case. PoRA either negotiates with the client until a feasible solution, or that the client steps back because of too high prices or other decisive demands of PoRA.

Corporate Strategy The objective of this department is to identify relevant trends and developments that impact the port and translate this into a strategy: the Corporate Strategy (CS).. This strategy must contribute to a long-term viability, economically and social added value of the port. The CS consists of two parts. The first part describes the current trends and developments and the impact of them on the port area -and a competition analysis of the position of the port area compared to other ports. The second part consists of the mission, vision and objectives of PoRA and how PoRA is going to reach these objectives. The corporate strategy (CS) is a result of a process that is currently quite independent from the 'Haven Ontwikkelings Cyclus'.

3.2 Challenge identification

Within the process that is described in the previous paragraph, PoRA faces multiple challenges. Based on the interviews with experts, these challenges are formulated. The challenges are numbered, which allows these to be used in following chapters.

Qualitative scenarios
In order to see which parameters are included in the qualitative scenarios a schematic overview is made of all parameters included in the qualitative scenarios. The parameters are grouped based on the subject and context of the parameter. A schematic overview of the qualitative scenarios is shown in Figure 6, in which the factors themselves are indicated with the blue bars.

[6] Opslag: extra costs per year to pay for the investment, which is not a loan because the investment will remain from the PoRA.

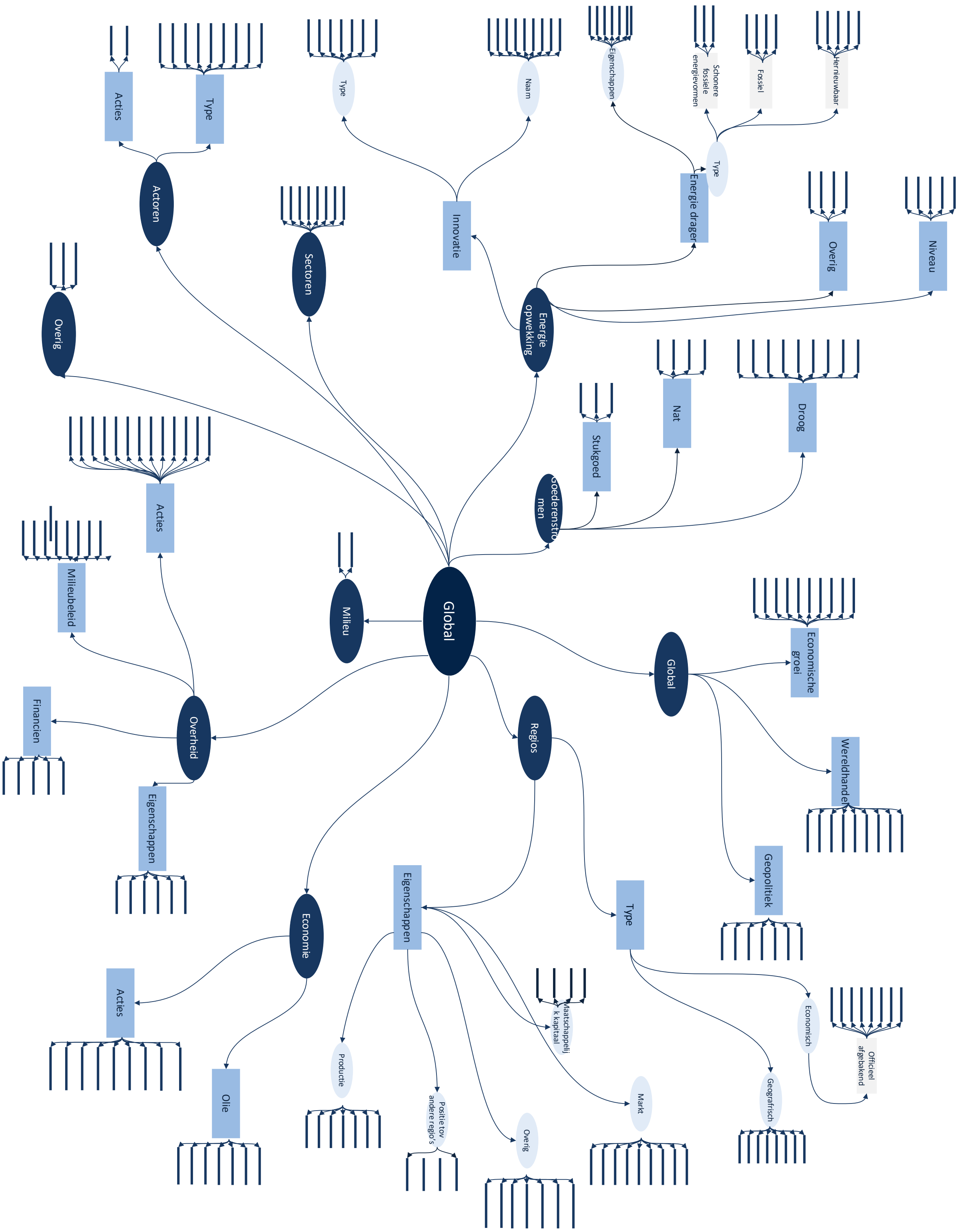


Figure 6: Schematic overview of the qualitative scenarios

In Figure 6 it becomes clear that the qualitative scenarios are detailed and an enormous amount of parameters is included. Synonyms or related terms are used interchangeably (challenge 1). This will be explained using the example of 'regions', of which the detailed overview is shown in Figure 7.

Three types of regions are used: officially demarcated geographical regions, non-officially demarcated regions and economic related regions. Especially the second group of regions are vague and not clearly demarcated regions. Within the economic group of regions synonyms and sub regions are used interchangeable. It becomes clear that a systematic approach is missing and that there is a lack of consistency. A second drawback of these qualitative scenarios is that they are expert dependent, which means that the variables taken into account depend on the expert who developed the scenario (challenge 2). Moreover, the scenarios for the different cargo types are developed by different experts, which leads to inconsistency between the different cargo types (challenge 3). The third drawback named by several respondents concerns the communication around the qualitative scenarios, communication concerning the use of scenarios is not always as intended. People tend to stick too much to calculating and getting the exact figures (challenge 4), while scenarios are actually made to discover and explore possible futures and ranges of possible outcomes. The translation of the 'world view' to the system of the Port area is also indicated as a challenge (challenge 5).

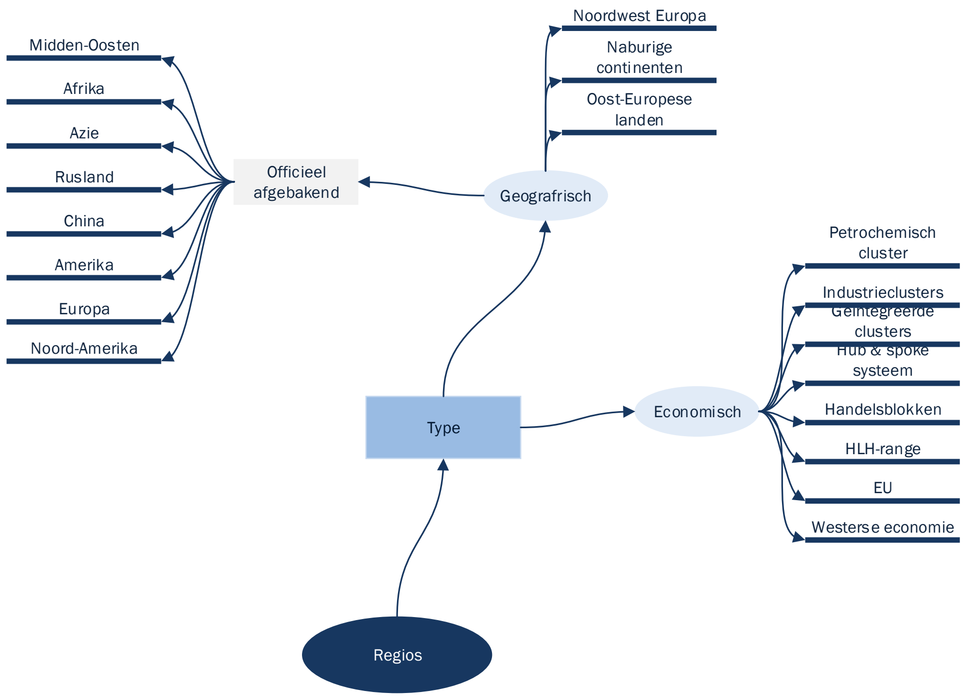


Figure 7: Type of regions in qualitative scenarios

Next to the information gained from the interviews, in literature some remarks are made about the traditional method for scenario development which also apply for PoRA. PoRA suggests that they 'forecast', but in order to forecast, you need to know something about the probability and likelihood. Several authors claim that it is impossible to say something about the exact likelihood (Booth, 2006) (Bryant & Lempert, 2009). It is also stated that a large number of interdependent uncertain factors can cause troubles when the traditional method of scenario development is used, as you cannot capture all plausible futures in a limited set of scenarios (Greeven et al., 2016). And because uncertain factors are grouped on beforehand, some interesting possible combinations of uncertainties may be lost (Kwakkel & Jaxa-Rozen, 2016). *Traditional scenario development has an inability to grapple with the long-term's multiplicity of plausible futures* (Hamarat, Kwakkel, & Pruyt, 2013). As different experts construct the scenarios, they will all have a different point of view, and come with different variables and parameters - this can be misleading (Halim, Kwakkel, & Tavasszy, 2016a). Traditional scenario development may work in smaller groups but in the case of the PoRA, where a large variety of stakeholders is involved, this method may not be optimal (Bryant & Lempert, 2009) (challenge 6).

Translation from qualitative to quantitative

As mentioned in the previous sub-paragraph, a large variety of parameters are included in the qualitative scenarios. However, when looking at the quantitative scenarios, the number of parameters taken into account is a lot lower (challenge 7). PoRA suggests that a large part of the variables from the qualitative scenarios would be translated to the quantitative scenarios, while this is not the case. This means there is no consistency between the qualitative and qualitative scenarios. A second challenge from the translation is the use of Excel, which has several drawbacks. Because Excel is used, the development of quantitative scenarios needs to be done manually, which makes it labour-intensive and error-prone (challenge 8, 9). For every cargo type, a separated Excel file exists which all have a different structure (challenge 10). Added to that, not all Excel files are linked completely automatically, so when numbers in one file are changed, they need to be corrected manually in the other Excel files (challenge 11). Another important drawback from using Excel is that the scenarios are not updated continuously, which makes them static (challenge 12). The scenarios are a snapshot of the information that is available on that particular moment. And because these scenarios are made manually, only the extreme parts of the scenarios can be calculated (challenge 13). Agreement about particular figures (challenge 14) or changes of figures are not well-documented (challenge 15).

Overslag Prognose Model

The division of throughput over the terminals is currently done based on the historical data of the terminals, adjusted by the expected growth rate of the total throughput. And a business manager can indicate an expected expansion or reduction of capacity of the terminal. However, the choice of liners for a particular terminal will not remain constant during 40 years and this liner choice is not included in the model (challenge 16). A second drawback is the fact that the redistribution of throughput over the different terminals in OPM needs to be done manually, which is again expert-depended, error-prone and time-consuming (challenge 17, 18, 19, 20). The data that is used for the expected changes in terminal capacity and other client information is not stored at one central place; most information is only stored at the OPM or the knowledge 'in the head of employees' (challenge 21). The output of the OPM is the expected throughput divided over the terminals and is accurate to 3 decimal places. This insinuates that the base data is accurate too, which is not the case (challenge 22). Another challenge is that there is no dynamic change of throughput to terminals. Throughput is calculated based on the current throughput adjusted by the growth rate (challenge 23). Another drawback from the OPM is, that train throughput can be assigned to a terminal without a train connection (challenge 24). The last challenge concerns a practical issue, during the handling of the shipbroker when the throughput enters the port area. The shipbroker needs to fill in a form, but he can make a mistake. He, then, assigns the cargo to a different terminal, while this is not the case. This causes the fact that the data gets polluted, which could case miscalculations in forecasts (challenge 25).

Port design development

The first challenge experienced by this department is the transfer of information from BAI (the output of the OPM) to PD. The output from the OPM is in Excel, however, this is not the correct format for the Excel model PD is using (challenge 26). Therefore PD needs to adjust this Excel file manually before using it, which is a time consuming process. The process of developing a future port design on itself is also a labour intensive and time consuming process (challenge 27). Consequently, PD is only able to develop one future port design instead of the desired five designs (one design for every scenario) (challenge 28).

Port Optimizer

In the port optimizer tool that is currently in development, the future port designs will be created manually. This tool performs a quick scan of infrastructure and environment. If this scan is negative, the port developers need to adjust their design manually (challenge 29). Even though the process is considered more efficient than the current (completely) manually Excel-made port designs, the process is still time-consuming (challenge 30) and still limits the ability to develop a large variety of future port designs and test them under different scenarios (challenge 31).

Environmental check

In the current process, an environmental check is done on the expected transportation movements. The production part of for example factories is mostly left out of scope (challenge 32). This is because PoRA has no figures about the exact production of these companies within the port area. Another challenge is the fact that in order to meet the requirements of the province, the scenarios that are used to calculate whether the new design fits within the zoning plan need to be the extreme scenarios. However, the most extreme scenario (in terms of emission, noise etcetera) developed, is not the same as 'maximum' possible activity at these area (challenge 33).

Communication BAI/PD/Infra/Environment

Because every department uses its own models and (partly) its data and has its own way of working, communication between the systems of the departments is difficult. At this moment, it is not possible to automatically communicate between systems and exchanging data asks a lot of effort from all the different departments (challenge 34). Adding to that, a lot of proceedings need to be performed several times. BAI sends information to PD, PD to infrastructure and eventually the environment departments performs the last check. If the outcome of the last check is negative, BAI needs to re-distribute the throughput again and the process starts again from the beginning (challenge 35).

Feedback port design, forecasts and corporate strategy

Most of the objectives defined in the corporate strategy are related to the throughput of the different cargo types of Rotterdam. In this current decision-making process forecasts are made by the BAI department. Based on these forecasts, a future port design is made. However, there is no feedback from the port design to the forecasts to see whether the future port design will contribute to the objectives from the corporate strategy (challenge 36).

Business case assessment

For financial calculations the currently used scenarios are not complete enough (challenge 37). If the issue of land changes, the price of renting space in the port area also changes. If there is little demand for energy, there may be land returned to the municipality for something else. In the forecasts, these price changes are not taken into account. When the forecasts of extreme scenarios are calculated with current prices, wrong conclusions will be drawn.

Corporate Strategy

In order to analyse the CS it is translated into an objective tree. The full objective tree can be found in appendix C. Both the objectives and the 'we have succeeded if' are demonstrated. The objectives in the CS do not have a measure unit, this is added in the objective tree.

Figure 8 gives an example of one of the objectives. In this figure the challenges in this objective tree are indicated with a number.

1. Not every objective has a 'we have succeeded if' measurement criterion (challenge 38).
2. Not all 'we have succeeded if' measurement criteria contribute to one of the objectives (challenge 39).
3. Not all 'we have succeeded if' measurement criteria are measurable (challenge 40).

The objective marked in orange, is the only objective that has a 'we have succeeded if' measurement criterion, which is also measurable.

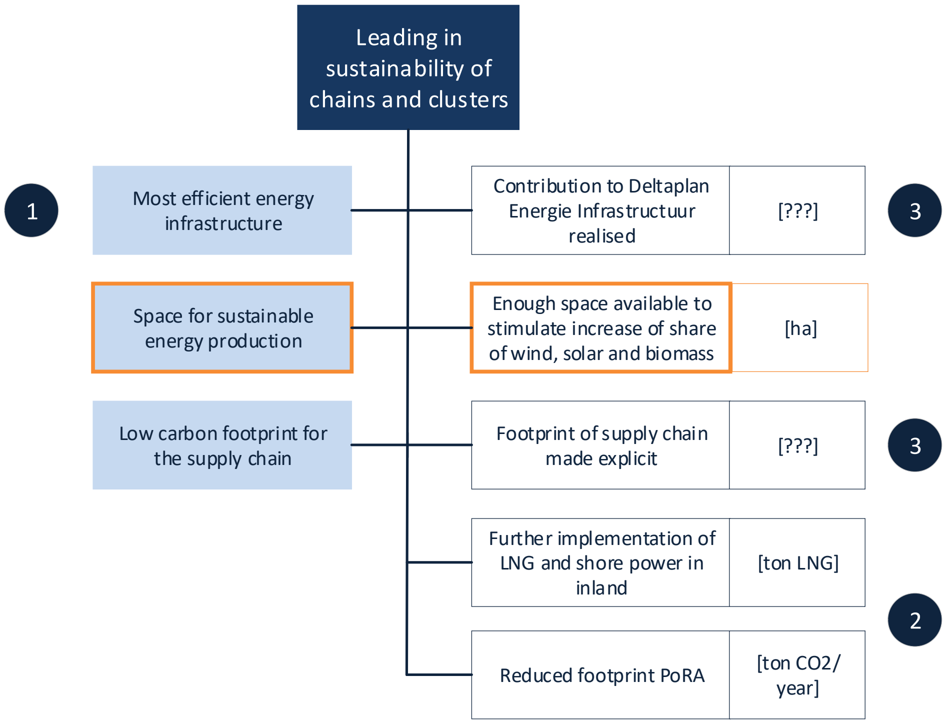


Figure 8: Example objective of CS

3.3 Conclusion

The sub-question that is addressed in this chapter is:

How is the current decision-making process of the Port of Rotterdam Authority organised and what are the challenges encountered in this process?

Based on interviews with experts this question is answered. The answer to the first part of the question, how the current decision-making process is organised, is presented in Figure 5. The main elements in this decision-making process are:

- development of long-term global forecasts
- development of port designs
- perform environmental checks
- assess infrastructural capacity
- develop the corporate strategy
- assess proposed projects.

The second part of the question is answered by defining the challenges that are faced by PoRA. In Table 2 an overview of these challenges is given, grouped per process element.

Table 2: Overview of challenges encountered by PoRA in their decision-making process

Development of qualitative scenarios
1. Inconsistency in terminology of qualitative scenarios
2. Expert dependent
3. Inconsistency between the different cargo types
4. Mind set of calculating and getting exact right figures in scenario use
5. Translation of world view
6. Traditional method of scenario development
7. Inconsistency between qualitative and quantitative scenarios

Use of Excel in qualitative scenarios
8. Development of scenarios labour intensive
9. Development of scenarios error prone
10. Not all cargo types have same structure in documents
11. Different documents not linked automatically
12. Not updated automatically, static
13. Only extreme parts of scenarios can be calculated
14. Agreement about particular figures not well documented
15. Changes of figures not well documented

OPM
16. Liner choices are held constant
17. Redistribution of TP in OPM manually
18. Redistribution of TP expert dependent
19. Redistribution of TP error prone
20. Redistribution of TP time consuming
21. A lot of information not centrally stored, but in 'the head' of the employees
22. Forecasts about tp to terminals is very exact (3 decimals), while the base data is not even exact
23. No dynamic changes of terminals, just growth rate
24. Errors with modalities
25. Miscalculations due to mistake of shipbroker

Port design development
26. Manually adjusting data to obtain right input
27. Port design process labour intensive and time consuming
28. Only able to develop one future port design

Port optimizer
29. Manual handlings in Port optimizer
30. Port optimizer still time consuming

31. No possibility to develop wide range of port design and test them under different scenarios

Environmental check

32. Production part is left out of scope
33. Difficult to match province demands

Communication between departments

34. Communication between systems of different departments is difficult
35. Inefficient loops in process
36. No feedback from forecasts to corporate strategy

Business case assessment of new projects

37. Currently used scenarios are not complete enough, no dynamic price taken into account

Corporate strategy

38. Missing 'we have succeeded measure'
39. Not all 'we have succeeded measure' contribute to an objective
40. Not all criteria are measurable

The model ecosystem that is designed in the next chapter, is based on this process. The different elements of the process are translated to components within the model ecosystem. The process elements and challenges are also used to define the requirements and specifications of the model ecosystem.

4

Design of the model ecosystem (level 1 and 2)

As mentioned in Paragraph 1.2, a model ecosystem is developed, which makes it possible to answer the second research question: *In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process*? The first steps in this development, are to define the specifications of a model ecosystem and to design one. In the previous chapter the most important elements within the decision-making of PoRA and the challenges faced within this process are defined. In this chapter these process elements and challenges are translated to requirements and specifications, which are used to develop the high-level design (level 1) and the logical design (level 2). In the first paragraph the requirements and specifications are defined. In the second paragraph, the various model ecosystem components are explained and a high-level design of the relations between these components is developed. After that, this design is explained in more detail. In the last part, a more detailed design is developed: the logical design (level 2 of the model ecosystem).

4.1 Systems engineering requirements statement

Before a model ecosystem can be designed, the requirements and specifications of this model ecosystem need to be defined. In order to do so the 'systems engineering requirements statement' of Sage & Armstrong (2000) is used. This statement contains, among other elements, the objective of the system, the functional and non-functional requirements and system specifications.

4.1.1 Objective of the model ecosystem

In the current decision-making process, PoRA struggles with making decisions based on and supported by models. Some models already exist, but the form of the models may make it difficult to extract the right information and to use them in an appropriate way. The objective of the model ecosystem therefore needs to be:

'A model ecosystem that supports the Port of Rotterdam in their decision-making process by providing information about the impact of possible futures on the port area, on the business value of the Port of Rotterdam Authority and on business cases'

4.1.2 Requirements

Two types of requirements are defined before the design can be started. The first type of requirements are the functional requirements. The functional requirements are a description of the functions the design has to provide in order to reach the objective (Herder, 1999). *'Because purposeful activity is a basic characteristic of any system, the systems engineer designs a system to accomplish specific tasks or functions. A function is a definite, purposeful action that a system must accomplish to achieve one of the system's objectives.'* (Sage & Armstrong, 2000, p. 128). The second type of requirements are the non-functional requirements. These requirements are not describing what the model ecosystem should do to reach the objective, but how these actions will be performed. In this research the non-functional requirements will be named as 'user requirements' and are brought forward by the employees of PoRA. The user requirements will be translated to system specifications, which are properties that the system needs to have (Sage & Armstrong, 2000).

Functional requirements

The model ecosystem should at least contain the functions that are present in the current decision-making process. The functional requirements are, therefore, based on the process elements defined in Paragraph 3.1. In order to reach the objective stated in the previous paragraph and to contain the functions of the current process, the model ecosystem needs to be able to perform the following actions:

- demonstrate possible futures
- calculate business case
- estimate the business value of PoRA
- determine the division of throughput over different terminals
- define the environmental impact of changes within the port area)

- o define the infrastructural impact of changes within the port area
- o determine safety areas, bottlenecks and opportunities.

In Chapter 1 it is mentioned that one of the difficulties in modelling a model ecosystem, is the difference in scale. For PoRA one of these scale differences can be found in the translation from global forecasts to forecasts for Rotterdam. An additional functional requirement, to solve this multi-scale issue, is therefore:

- o translate global forecasts to forecasts for Rotterdam.

In order to perform these actions, the model ecosystem needs to:

- o contain information about the environment and other factors influencing the port area
- o contain information about current port characteristics
  - physical (infrastructure, customers, etc.)
  - financial (port dues, renting price etc.)
- o contain information about environmental restrictions
- o contain information about the various cargo types
  - production
  - throughputs
- o contain information about expected port performance
  - market share.

Non-functional requirements (user requirements) and system specifications

In Chapter 3 an analysis of the current system is conducted. The result of this analysis is a list of challenges encountered by employees of PoRA. This list of challenges is translated to a list of user requirements, which can be translated to a list of specifications for the design. The challenges are grouped, and based on the topic of these groups, the user requirements are defined. This translation of challenges, to requirements, to specifications is shown in Figure 9 and is explained in more detail in the following paragraphs.

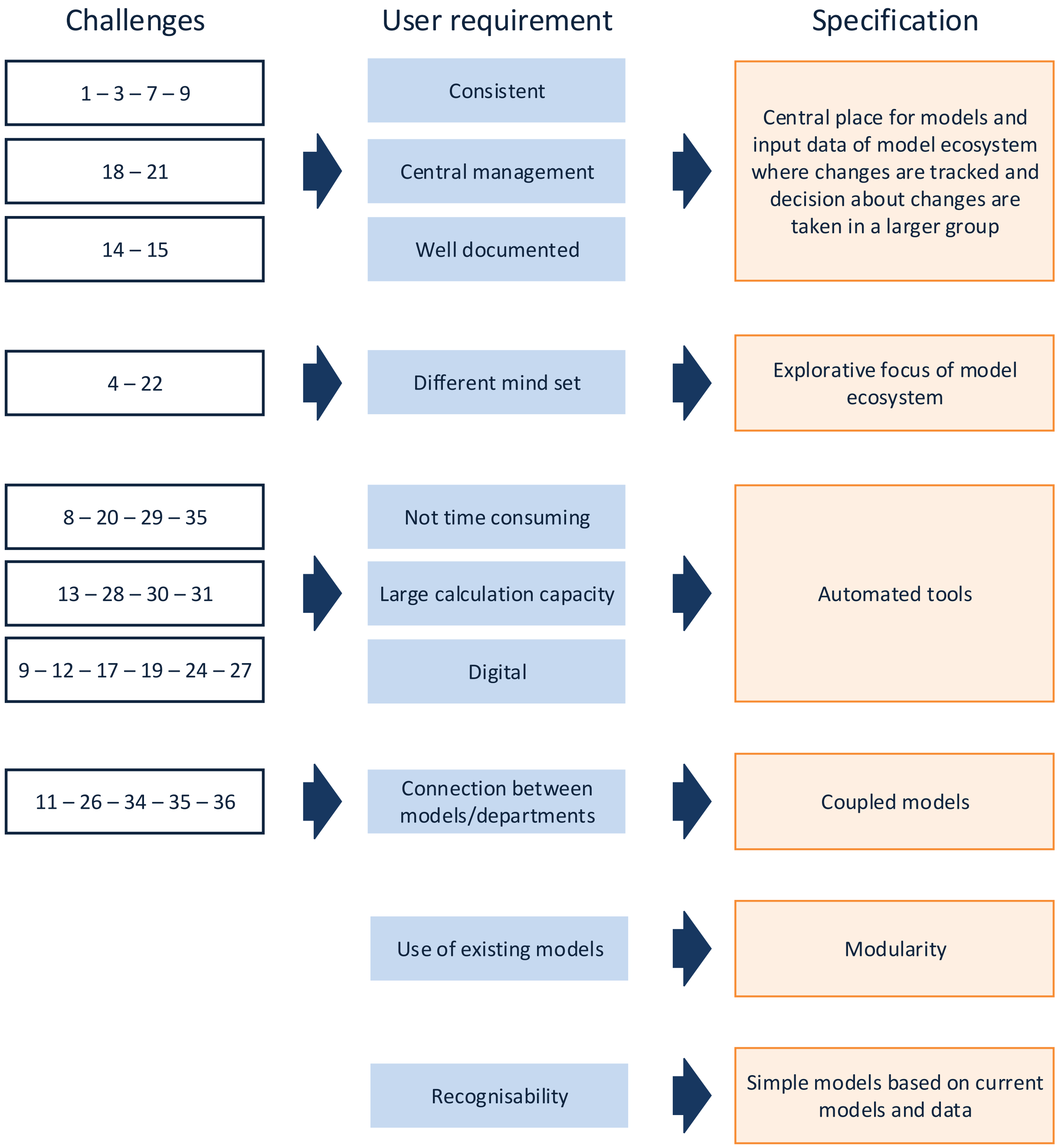


Figure 9: Translation of requirements to specifications

Central place for models of model ecosystem and data When models are developed at a central place, where experts from different departments negotiate about the content of the models, the models will be less dependent of the input of a single expert. The agreements made during these negotiations need to be documented at a central place and all adjustments that are made, need to be documented, as well. This central management should help to prevent the development of individual ideas which are not communicated, which could lead to inconsistency on the long-term.

Automated tools An important step to improve the use of models in the decision-making process is to develop automated simulation tools. These simulation tools give the ability to represent a real and complex system in an abstract model (Riexinger et al., 2015). These automated tools are labour-intensive to develop, but will save time when they are in operation. They also ensure that less manual operations need to be performed. It is of importance that these automated tools have a large calculation capacity (computing power), in order to explore a wide range of possible futures.

Coupled models When models are coupled, it will not be necessary anymore to afterwards adjust output data manually when two systems need to communicate. It does, however, ask for more effort in the development face because different formalisms need to be adjusted in such a way that they can communicate with each other.

Explorative focus of model ecosystem A mental shift needs to be reached: exploring possible futures, uncertainties and solutions rather than indefinitely calculating one scenario and treating this scenario as 'the future'. As it will be about exploring, rather than on calculating exact figures, it ensures that the use of models within the process is less sensitive for expert dependent knowledge.

Modularity In order to implement the already existing model, the model ecosystem needs to be a hybrid model in which the different components can be easily replaced with other models. In order to do so, it needs to be very clear what the input and output of the different components are. That if a model will be replaced, it should be clear what the new model will receive as input and what it should give as output. The model ecosystem should therefore contain a high degree of modularity. Whereby existing models can be used, different components of the ecosystem can be designed individually by different types of experts, and components are easily replaceable by new models (spec: modularity). This modularity allows PoRA to improve, adjust or expand the existing models by the experts who have most knowledge about these components.

Use of simple models More complex and more detailed models are not always 'better models". What is of importance is that users of PoRA recognise the relations that are simulated, and the data that is used.

Strict defintion of input and output requirements of the components. By designing a model ecossystem in which the inputs, outputs and data to be transered are clearly defined, the underlying models are can change easily. In the design it more import what the outcomes of de components are, rather than how particular outcomes have come about. Because the input and output requirements are defined very strict, adjustments or replacement of a component will not impact the type of outcome.

4.2 High-level design (level 1)

The functional requirements that are defined in the previous paragraphs, are grouped based on their role within the decision-making process. Based on these groups, the components of the model ecosystem are defined. This translation of functional requirements to components is shown in Figure 10.

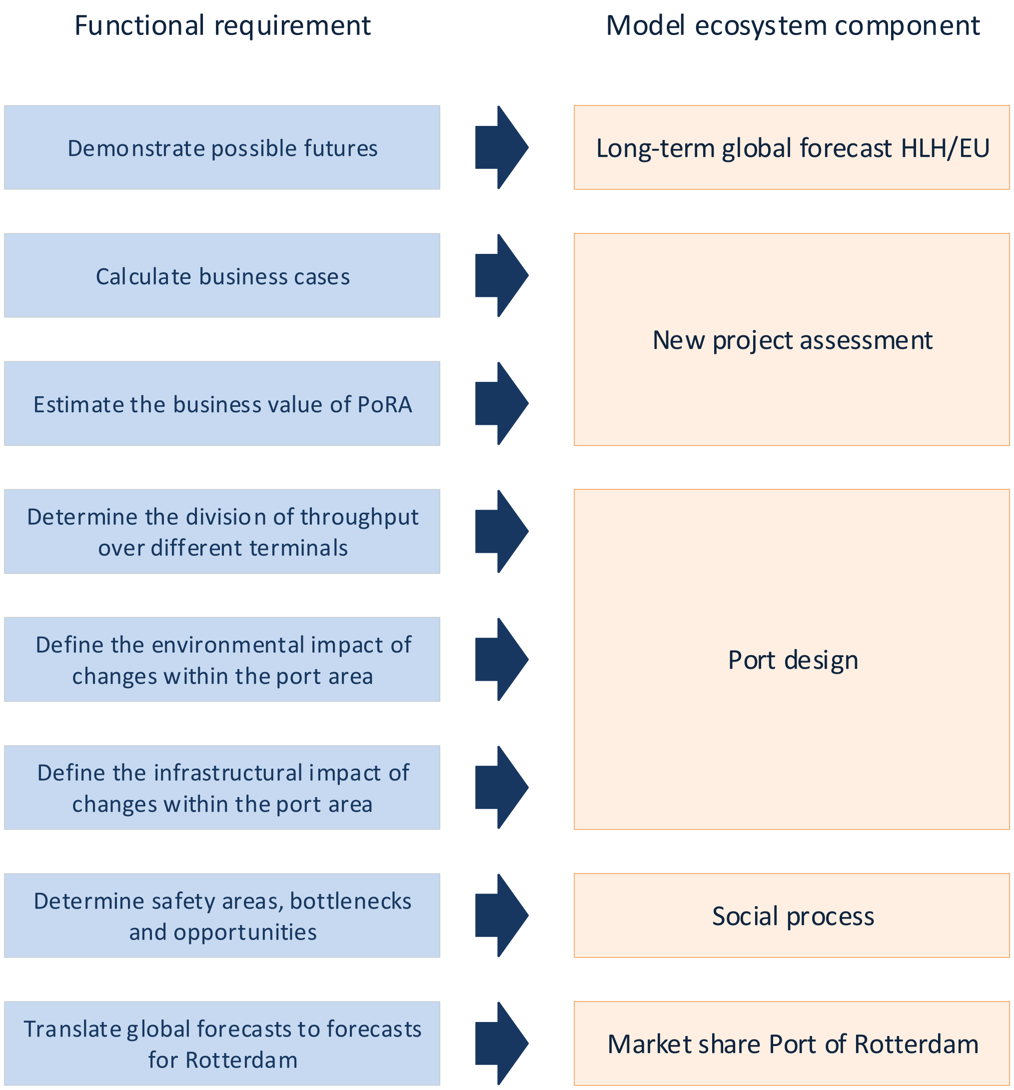


Figure 10: Translation of functional requirements to model ecosystem components

Each component gives input for the other components and receives input back. These different components all have their individual function, objective and purpose. However, *'When a system is* *taken apart its essential parts lose their ability to carry out the function they have in the whole'* (Gharajedaghi & Ackoff, 2003, p. 3). This means that the individual components need to be integrated so that they, together, contribute to the overall function of the system and form the high-level design of the model ecosystem. As a result, the components will be interrelated and connected to one another. To obtain more clarity, a preliminary conceptual design, resulting in a high-level design, is developed in which a foundation is laid for the model ecosystem. In this high-level design, the objective of the different system components and the conceptual relations between these different components are made explicit. In this design, it is also indicated on which points data is exchanged and what kind of data this is. In this high-level design, it can also be easily seen on which locations within the model ecosystem KPIs should be measured. In the following paragraphs, the five components will be discussed in more detail. The design of this high-level design was an iterative process in which several conceptual designs were developed. Together with PoRA, it is decided which high-level design was most suitable. The final high-level design is shown in Figure 11.

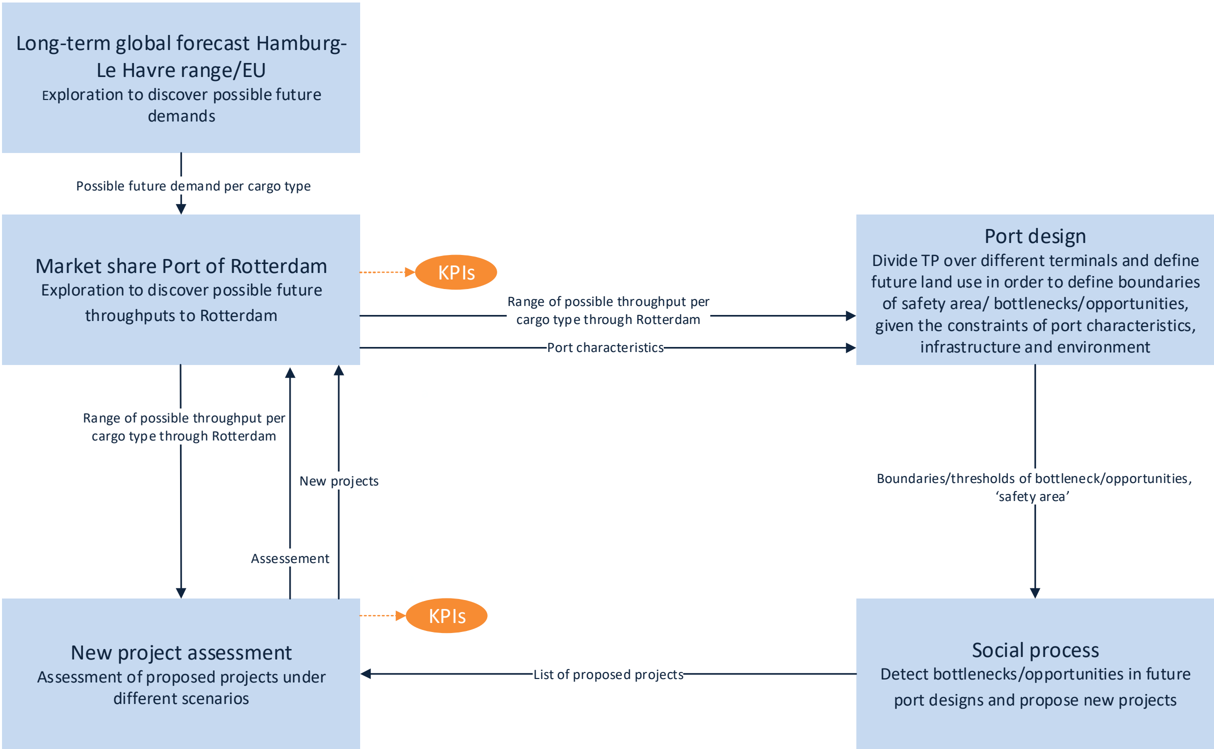


Figure 11: High level design (level 1)

Long-term global forecast Hamburg-Le Havre range/EU and market share Rotterdam

In the 'long-term global forecast Hamburg-Le Havre range(HLH)/EU' component, the expected demand for the HLH/EU region will be calculated. For every cargo type a separate model will be developed. In the 'Market share Rotterdam' component this expected demand is translated to throughput for Rotterdam, based on the market share of Rotterdam. These two components together have the function of demonstrating possible futures regarding the throughputs for the port area.

Port design

This expected throughput to Rotterdam will be used as input for the port design to divide this over the different terminals and the different modalities. The port design component consists of three subsystems with the following functions:

- determine the division of throughput over different terminals
- define the environmental impact of changes within the port area
- define the infrastructural impact of changes within the port area.

This component has three main functions:

- determine ranges within which the current port design is 'safe' (that is to say: no adjustments are required)
- determine thresholds/ranges where bottlenecks exist
- thresholds/ranges where opportunities for the PoRA exist.

Social process

In this social process component the output of the port design component will be evaluated. Based on the bottlenecks and opportunities defined in the port design component, new projects will be proposed which contribute to solving them. The characteristics of the new project need to be defined in this component.

New project assessment

The projects proposed in the social process will be assessed based on the business case, the impact on the KPIs of PoRA and the bottlenecks or opportunities the project causes. The forecasted throughput to Rotterdam will be the input to evaluate proposed projects. When a new business case is made, this will be included in the port design (port characteristics), and because the output of the port design will be input for the market share to Rotterdam model, it can be evaluated whether the new business case has the intended impact. Once the proposed new project is approved, it will be included in the port properties permanently.

KPIs

The KPIs will be determined within the corporate strategy.

The commercial actions are included in model ecosystem to see what the influence these actions have on both the throughput to the port area and the final business value of PoRA on the short- and long-term.

4.3 Logical design (level 2)

At level 2, the (detailed) conceptual design of the different components is developed. In this design, the specifications defined in Paragraph 4.1 are translated to more detailed specifications of the different components (Sage & Armstrong, 2000). For every component, the following specifications are defined in more detail:

- general objective
- function
- output
- social component.

Since the components may consist of multiple elements, the following specifications are defined for every element:

- type
- purpose
- implementation
- knowledge and development
- input
- output
- scale
- time frame.

The specifications of the model ecosystem components and their elements are shown in Table 3. In Figure 12 these specifications are translated to a logical design of the model ecosystem.

A general specification for the model ecosystem concerns the determination of figures, relations and other model choices, the documentation of data, and changes to the model ecosystem. When particular agreements are made about characteristics of the model ecosystem, these agreements need to be well documented. The following characteristics need to be documented: the date, the content, and the involved employees. A centrally managed system needs to be developed where all these agreements and changes are tracked systematically.

Table 3: Specifications of the model ecosystem components

Long-term global forecast HLH/EU

General objective	Discover how certain changes in the world lead to changes in demand for a particular cargo type
Function	Explorative
Output	Range of possible future throughput per cargo type
Social aspect	

Elements

Element	Purpose	Implementation	Type	Knowledge and development	Input	Output	Scale	Time frame
Cargo type model	Define possible future demands of cargo type	Simulation model	System dynamics	Relations in model based on literature, real world and PoRA knowledge		Range of possible future demand of cargo type	Global/HLHrange/EU	Long-term

Market share Port of Rotterdam

General objective	Discover how certain changes in the world and in the port area impact the throughput to Rotterdam
Function	Explorative
Output	Range of possible future throughput per cargo type
Social aspect	The development of the model needs to be done with multiple experts

Data	Source
Financial port characteristics	Based on current properties
Physical port characteristics	Based on current properties

Elements

Element	Purpose	Implementation	Type	Knowledge and development	Input	Output	Scale	Time frame
Market share model	Define possible future market shares of Rotterdam	Simulation model	Agent-based	Relations in model based on literature, real world and PoRA knowledge	Range of possible future demand per cargo type Port characteristics	Range of possible future tp per cargo type	Port area	Long-term

New project assessment

General objective	Assess the profitability of proposed projects and the impact they have on the business value and other KPIs
Function	Assessment
Output	Assessed projects
Social aspect	The KPIs for the corporate strategy are defined through a process of negotiation The assessment of projects will be partly based on social considerations

Data	Source
KPIs	Corporate strategy
Case properties	List of proposed projects

Elements

Element	Purpose	Implementation	Type	Knowledge and development	Input	Output	Scale	Time frame
Business value calculation	Calculate business value	Simulation model	Mathematical calculation	Based on current process	Range of possible future throughput per cargo type Financial properties	Business value PoRA	Port area	Long-term
Business case calculation	Calculate business case	Calculation simulation model Enter case properties manually	Mathematical calculation	Based on current process	Range of possible future throughput per cargo type KPIs Financial properties Case properties	Profitability proposed projects	Port area	Long-term
Project assessment	Assess new projects	Manual operation	Assessment	Based on knowledge of experts and on financial strategy	Business value PoRA Business case new projects	New projects	Port area	Long-term

Social process

General objective	Assessment of future port designs and propose new projects
Function	Assessment
Output	List of proposed projects
Social aspect	The assessment will be done based on expert knowledge, experience and insights

Elements								
Element	**Purpose**	**Implementation**	**Type**	**Knowledge and development**	**Input**	**Output**	**Scale**	**Time frame**
Assessment of port designs		Partly automated, but assessment is human performance	Social process/model		Boundaries/thresholds of bottlenecks/opportunitie s, safety areas	List of proposed projects	Port area	Long-term

Port design

General objective	Define boundaries to detect bottlenecks/opportunities
Function	Multi-criteria satisficing
Output	Boundaries/thresholds of bottleneck/opportunities, 'safety area'
Social aspect	

Data	Source
Key figures	Facts
Policies	Government
Spatial plan	Municipality
Modal split	Historical data

Elements								
Element	**Purpose**	**Implementation**	**Type**	**Knowledge and development**	**Input**	**Output**	**Scale**	**Time frame**
Satisficing division of throughput and land use	Distribute throughput over different terminals. define future land use	Simulation model	Multi-criteria satisficing	Relations in model based on literature, real world and PoRA knowledge	Range of possible future throughput per cargo type Physical port properties Outcome Infra/environment check Modal split	Range of TP/terminal/cargo type Boundaries/thresholds of bottlenecks/opportunitie s, safety areas	Port area	Year
Environmental check	Assessment/calculatio n whether input fits within environmental constraints	Simulation model	Assessment	Relations in model based on literature, real world and PoRA knowledge	Number of vehicles (trucks, trains, barges) Range of TP/terminal/cargo type	Yes/no	Port area	Year
Infrastructural check	Assessment/calculatio n whether input fits within current infrastructural capacity	Simulation model	Assessment	Relations in model based on literature, real world and PoRA knowledge	Physical port properties Range of TP/terminal/cargo type	Number of vehicles (trucks, trains, barges) Yes/no	Port area	Year

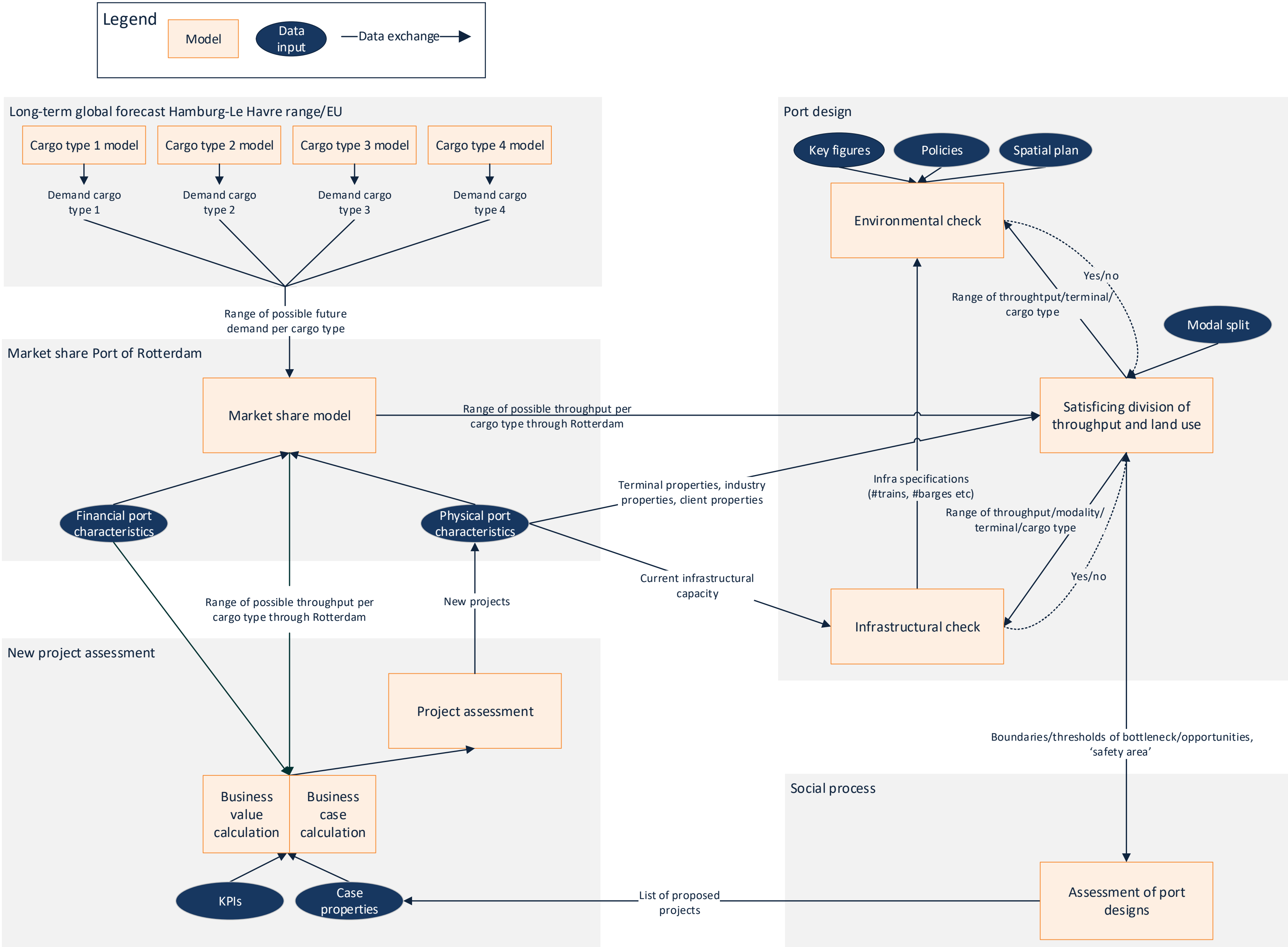


Figure 12: Logical design (level 2)

4.4 Conclusion

In this chapter a model ecosystem is designed. The first steps in this development are to the define what the specification of a model ecosystem are and to design a model ecosystem. Based on the outcomes of Chapter 3, the functional requirements and the non-functional requirements are defined, which are translated to system specifications. The functional requirements of the model ecosystem are:

- demonstrate possible futures
- calculate business cases
- estimate the business value of PoRA
- determine the division of throughput over different terminals
- define the environmental impact of changes within the port area
- define the infrastructural impact of changes within the port area
- determine safety areas, bottlenecks and opportunities
- translate global forecasts to forecasts for Rotterdam.

The system specifications of the model ecosystem are:

- central place for models of model ecosystem and data
- automated tools
- coupled models
- explorative focus of model ecosystem
- modularity
- use of simple models
- strict defintion of input and output of the components.

These requirements and specifications are used for the development of the high-level design and, eventually, the logical design. These designs of the model ecosystem consist of five components, which all relate to one (or multiple) functional requirement:

- long-term global forecast HLH/EU
- market share Port of Rotterdam
- port design
- new project assessment
- social process.

These designs are shown in Figure 11 and Figure 12.The following requirements and specifications are included in these designs:

- all the functional requirements
- modularity: because the components are designed as individual elements (communicating with eacht other), they can be easily replaced by other elements
- coupled models: the five components are coupled to one another
- strict defintion of input and output of the components: for each component it is defined which input is required from the other components and what output it generates.

In the next chapter a proof of concept will be developed by applying this design to the coal case of PoRA, which support the answering of the second research question: *In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process*?

5

Design and implementation of a proof of concept

In the previous chapter a high-level design and a logical design are developed. In this chapter a proof of concept of this design is developed. This is done by applying the design to the coal case (Chapter 1). The first step in the development of this proof of concept is to define the scope. A large variety of decision types exist within this coal case, and not all of them are taken into account within this research. The second step is the development of a detailed design of the individual components (level 3 of the model ecosystem). In these detailed designs of the components, the factors included in the component and the conceptual relations between these factors are defined. The next step is the operational implementation of these detailed component designs. The last step in the development of the proof of concept is the coupling of the five components.

5.1 Scope of projects in the proof of concept

Every year, multiple decisions are made by PoRA about new projects within the port area. These projects range from the establishment of new companies in the port area, to the construction of new infrastructure to more commercial related projects. Because not all projects regarding the coal case can be taken into account in this research, the scope of the proof of concept will consist of three types of projects:

- issue of land for coal terminals
- new infrastructure funded by PoRA
- commercial action of PoRA.

Issue of land for coal terminals Three categories of land issue projects exist:

- new terminal
- expanding/shrinking existing terminal
- closing existing terminal.

The issue of land for coal terminals is done together with the business managers.

New infrastructure funded by PoRA In the port area a large variety of infrastructural projects exist. Some examples from the last few years are: the Theemswegtracé, the widening of the 'Breeddiep' and the deepening of the 'Nieuwe Waterweg' (Port of Rotterdam Authority, 2015). The projects within the scope of this project concern the following three types of infrastructural projects:

- road construction
- rail construction
- water way construction.

These projects will be included in the model ecosystem by changing the port characteristics. Either the road, rail or water way capacity of the areas and their corresponding terminals will be changed.

Commercial action of PoRA

Appendix PoRA I (commercial actions)

For the proof of concept, it is important that it can be assessed what the influence of commercial actions will be on the long-term performance of PoRA. The commercial actions will be included in the design under the port characteristics (financial characteristics), which can be adjusted in order to see the impact these changes could have on the long-term performance.

5.2 Detailed design and implementation of the components of the model ecosystem

The strength of the models of the different components will not be the details. The strength of the models will be the ability to translate a particular structure of the system into a simulation model to explore possible outcomes (Bankes, 1993). The sub models will, therefore, be simplified models, which can be coupled to new and existing models. Within PoRA multiple simulation models already exist. Because one of the user requirements is the use of existing models, the existing models will be integrated into the new system. However, due to technical reasons, the existing models could not be coupled to the new models. It is, therefore, chosen to represent these existing models by simple equations. These equations will receive input from other ecosystem components, perform a calculation and give an output similar to the output of the existing models. Multiple ways of modelling a particular system are possible, for this research one of these possible models is chosen. An extended explanation of the implementation of the components can be found in Appendix E. The full software codes of the software models can be found on the Github.

5.2.1 Long-term global forecast EU/HLH range

The coal market is a complex market, consisting of a large number of interconnected factors, containing feedback loops, influenced by external factors and exposed to a lot of uncertainties. Several simulation models are developed to simulate the coal demand, which all include a large variety of factors (Bildirici & Bakirtas, 2014; Chan & Lee, 1997; Yu & Wei, 2012). Based on these models, a selection is made of the most import factors influencing the coal demand. Ideally the model would contain most of these factors and the factors named in Figure 6 (Chapter 3). But because the models within the proof of concept need to be simple models, it is chosen to reduce the number of factors in the coal demand model. Together with experts from PoRA and based on the uncertainties impacting the system, a selection of three variables is made: share other grey energy sources (mainly gas), energy demand and the share of green energy in the energy mix. In Figure 13, the relation between these factors is shown.

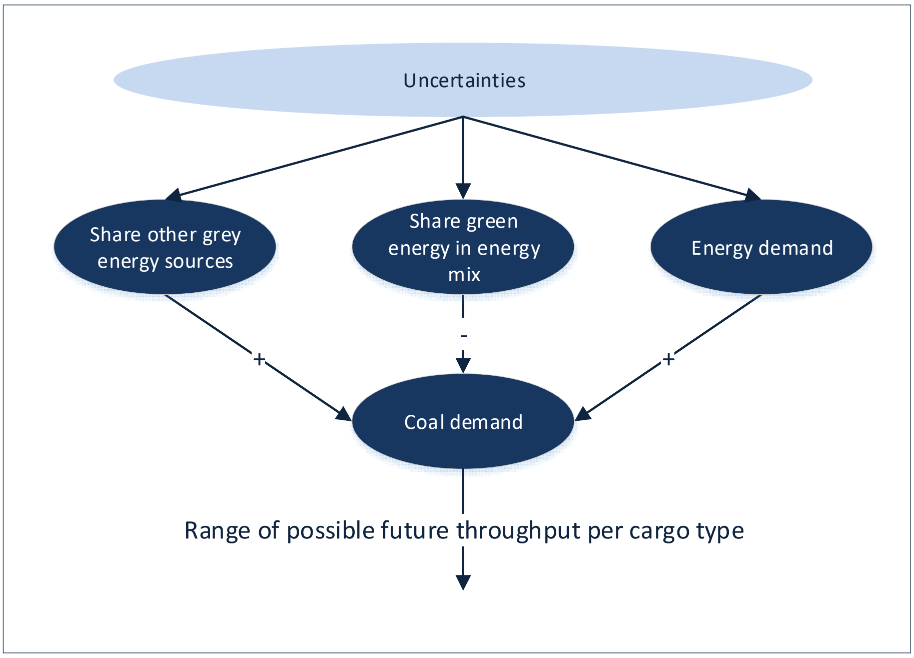


Figure 13: Long-term-global forecast EU/HLH range - coal case

Uncertainties in the coal demand

The last question of the expert interviews concerned the uncertainties the port area is facing. In Appendix D, the full list of uncertainties can be found. The main uncertainties regarding the coal case that came forward are related to the development of the energy market and are present in the long-term global forecast component. An overview of these uncertainties is shown in Figure 14.

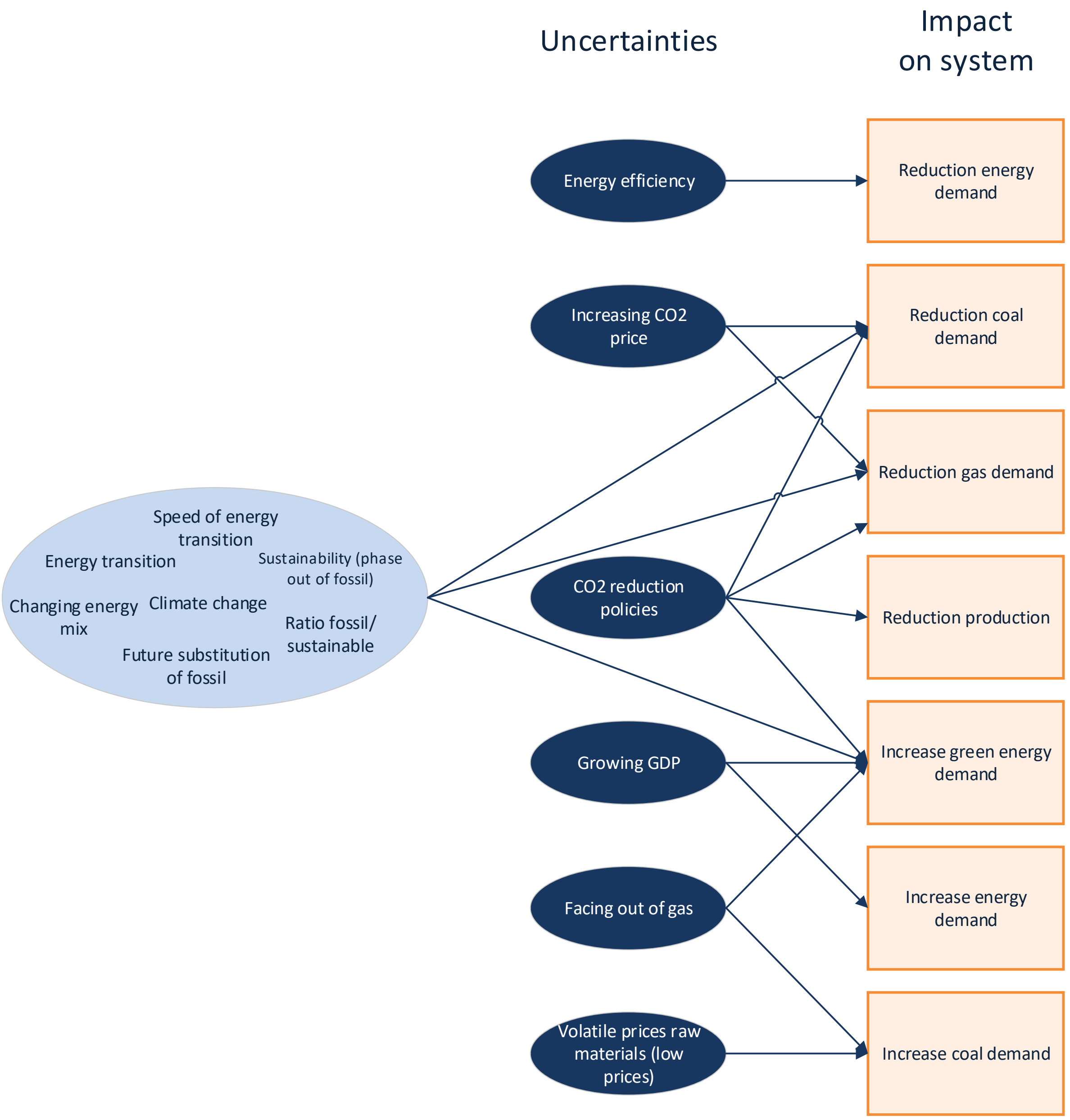


Figure 14: Uncertainties in the coal market

The impact these uncertainties have on the system is mainly on three factors: coal demand, energy demand and the share of green energy in the energy mix. How the influence of these uncertainties is established is left out of scope in this design. For this proof of concept it is in scope what the influence of these uncertainties is on the system. The translation of these uncertainties into the model will be by adding a bandwidth of the uncertain factors and to see what the influence is. Later, the meaning of subspaces within these bandwidth can be linked to a particular narrative. An example hereof is the energy transition: how this transition will accomplish is left out of scope. What does fall in scope is how the energy transition will influence the system, namely by influencing the share of green energy in the energy mix.

Operational implementation (software implementation)

The coal demand model consists of a set of equations implemented in Python. The coal demand is determined by three variables: the share of green energy (% of total energy demand), the share of other grey energy sources (% total grey energy demand) and the total energy demand. It is chosen to implement one uncertainty for every factor in de coal model.

$$Coal\ demand = (1 - share\ other\ grey\ energy\ sources) * (energy\ demand - (share\ green\ energy * energy\ demand))$$

Combining the energy demand, the share of other grey energy sources and the share of green energy in the energy mix, will obtain a large variety of possible future coal demand values (shown in Figure 15)

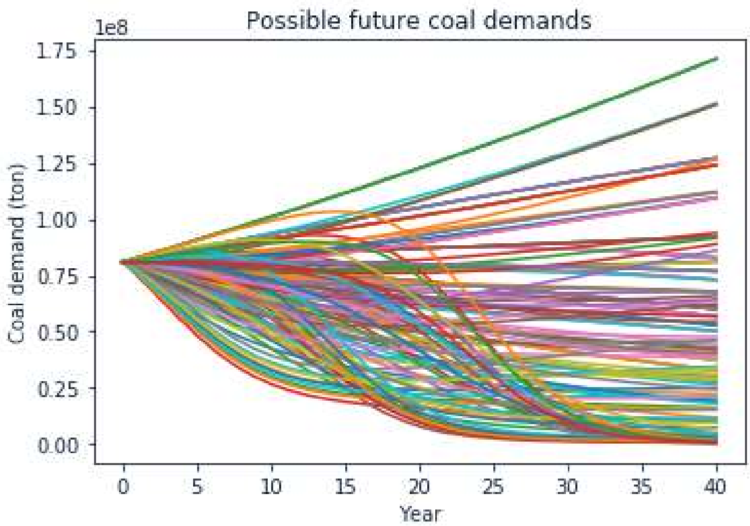


Figure 15: Possible future coal demands

5.2.2 Market share Rotterdam

The market share of Rotterdam consists of a base market share and a percentage that is influenced by the added value of the characteristics of the port. The added value market share will be determined by both the number of companies established in the port area and by the choice of companies to the port area. This second part of the market share will be determined by valuation of companies of several factors. Wiegmans, Van Der Hoest, & Notteboom (2008) performed a literature review to define the most important port characteristics influencing this port choice:

- port physical and technical infrastructure
- port efficiency
- interconnectivity of the port
- reliability, capacity, frequency and costs of inland transport services
- quality and costs of auxiliary
- efficiency and costs of port management and administration
- availability, quality and costs of logistic value-added activities
- availability, quality and costs of port community systems
- port security/safety and environmental profile of the port
- port reputation.

In Figure 16 the relations between these factors are shown.

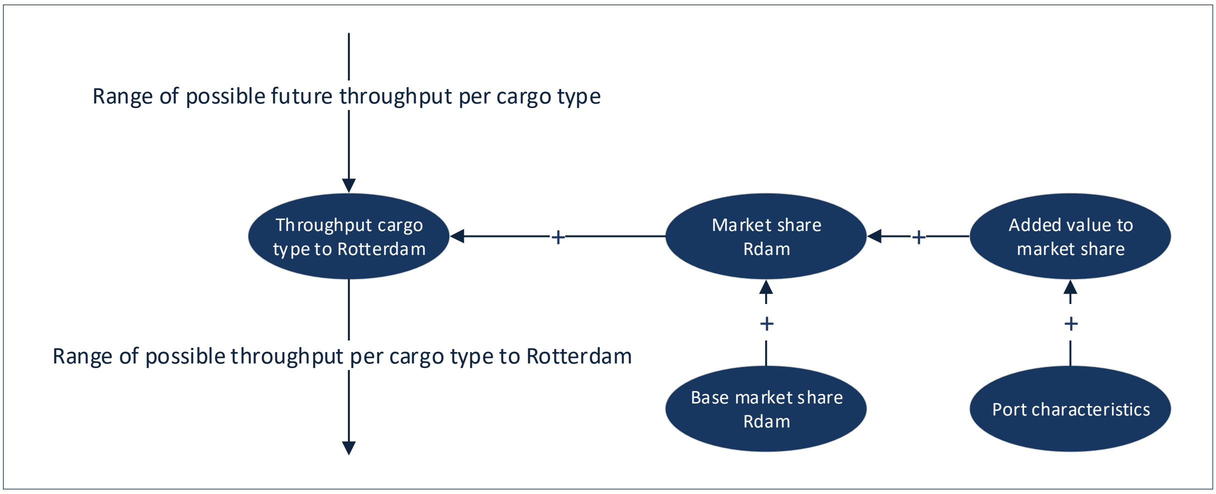


Figure 16: Market share Rotterdam model

Appendix PoRA II (commercial actions 2)

Operational implementation (software implementation)

In the ideal situation the market share Rotterdam model would be a choice based simulation model simulating the choice of companies for the Port area based on the port properties and other factors influencing this choice (e.g. alliances between lining companies). Due to time limitations, this choice based model consists of a set of equations implemented in Python.

$$Base\ market = initital\ base\ market\ share * (1 + growth\ factor\ base\ market\ share)^t,$$

$$where\ t = time, in\ years$$

$$Added\ value\ market\ share = percentage\ (determined\ by\ PoRA)$$

In this model, ecosystem the added value of a particular project needs to be estimated by PoRA itself. The added value of all the new initiated projects will be summed and added to the base market share. By combining different values of the variables, multiple values for the market share of Rotterdam are created. These possible values of market share are shown in Figure 17.

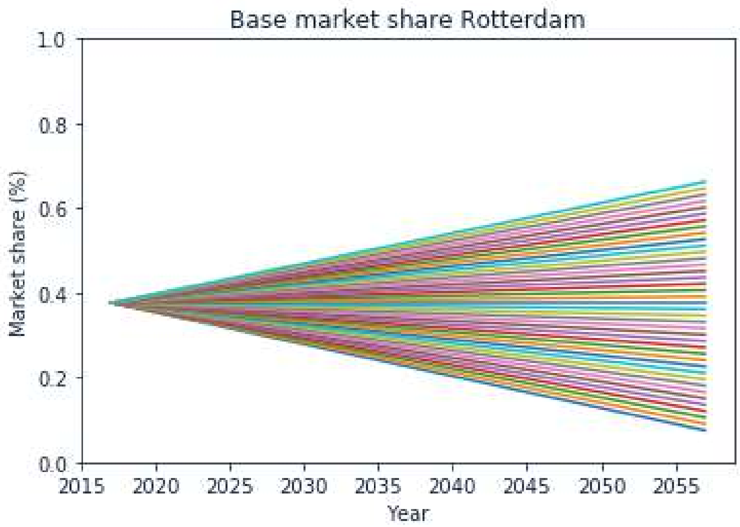


Figure 17: Total market share Rotterdam

5.2.3 Port design

Within the port design component, three subsystems exist. Currently, multiple models are used within these three subsystems. An overview of the different models and the software in which they are built is given in Table 4.

Table 4: Models used in port design component

Subsystem	Model	Software
Division of throughput	OPM	AIMSS
Environment	OPS	
	Landelijk stikstof model	Aerius
Infrastructure	Binnenvaart Logistiek model	Excel
	Rail simulation tool	Macomi
	Road traffic simulation model	Haskoning-DHV

The output of the OPM will be sent to the infrastructure department, which translates the throughput per modality to number of vehicles and evaluates whether the expected throughput fits within the current infrastructure. They send the number of vehicles to the environment department which on their turn assesses whether the expected throughput fits within the environmental limits. When the outcome is negative, the feedback goes back and the circle starts again. As mentioned in Paragraph 3.2, this feedback loop is inefficient. In order to overcome this challenges, the three subsystems of this component will be implemented in a more interconnected system.

Based on the terminal properties, the forecasted throughput and the infrastructural and environmental constraints, a satisficing division of throughput over the terminals and future land use will be defined. The definition of satisficing is: *"Examining alternatives until a practical (most obvious, attainable, and reasonable) solution with adequate level of acceptability is found, and stopping the search there instead of looking for the best-possible (optimum) solution"* (Business Dictionary, 2017). The forecasted throughputs are not 'the future', but possible futures. It is, therefore, of importance to see whether one of the possible distributions may fit, instead of finding the exact optimal distribution of throughput over the different terminals.

Next to implementing a satisficing model, a second design choice that contributes to overcome the challenge of calculating too much instead of exploring possible futures, is to approach the port as an area consisting of multiple smaller areas. Within these areas, several terminals are located. For PoRA, it is of importance to know whether the current design is suited for the different forecasted throughputs. The forecasts are uncertain and PoRA cannot steer all clients in a particular direction and, thus, cannot influence the division of throughput over the terminals completely. The focus should lie therefore, on analysing whether the forecasted throughput may fit within a particular area, rather than focusing on the exact division of throughput to one specific terminal. The areas used in this subsystem will be the same as the areas used in the Masterplan:

- Maasvlakte
- Europoort
- Botlek/Vondelingenplaat
- Waal-/Eemhaven
- Merwehaven- Vierhavensgebied.

The output of the satisficing model will be the input for the infrastructure subsystem, which will also give input to the environment subsystem.

Satisficing model The objective of the port design component is to evaluate whether the forecasted throughput can fit within the current port and if bottlenecks or opportunities may occur. Throughput will first be divided over the different terminals based on their historical market share. The throughput of the terminals in one area will be summed and it will be checked whether this total throughput will fit within this area. If this is not the case, it will be checked if there is any terminal within the area that has the possibility to expand. If so, one of these terminals will be randomly chosen to expand. If there is no terminal within the area with expansion possibilities, a random area will be chosen to start this procedure again, until all throughput is divided. If none of the terminals has enough capacity for the forecasted throughput, the throughput will be assigned as 'throughput without terminal', this will be an indication for PoRA of the capacity that is needed in a particular area for a particular cargo type.

Infrastructure The infrastructure calculation translates tons per modality to number of trains, barges and trucks. And checks whether the proposed division of throughput fits within the current infrastructural capacity. When it does not fit, the throughput will either be redistributed in order to fit or the model will identify this bottleneck. In the social process a project to expand the current infrastructure can be proposed.

Environment The environmental check assesses if the proposed division of throughput fits within the spatial plan and other environmental restrictions. When the throughput does not fit, it will either be sent to another terminal or, when no other terminal is available, it will be defined as 'throughput without a terminal'.

Coupling of the three subsystems The three models will be coupled, which enables the fact of performing the feedback loop between the subsystems more efficient. The expected throughput will be calculated, send to the infrastructure and environment model. This loop should be performed continuously.

Operational implementation (software implementation)

In the ideal situation, the OPM, the existing infrastructure and environmental models would be adjusted and coupled. Due to time limitations and scoping of the project, this could not be done. The models are replaced by simple simulation models, explained in the following paragraphs. These replaced models demonstrate the same dynamics as the existing models. In order to simulate the existence of multiple models in different software and demonstrate the possibility of coupling multiple models in different software tools, it was initially chosen to build these three replacing models in different software tools. The satisficing model was built in Netlogo and the infrastructure and environment models were built in R. The Netlogo model and the R models were coupled through the RExtension of Netlogo. However, the coupling made the run time performance decrease, and the PyNetlogo coupling was not able to run a Netlogo model coupled to an R model. It is therefore chosen to include the infrastructure and environment models in the Netlogo satisficing model. The subsystems are implemented in such a way that it is easy to replace these parts of code by the output of a separated simulation model. The logic of the entire Netlogo model is shown in Figure 18.

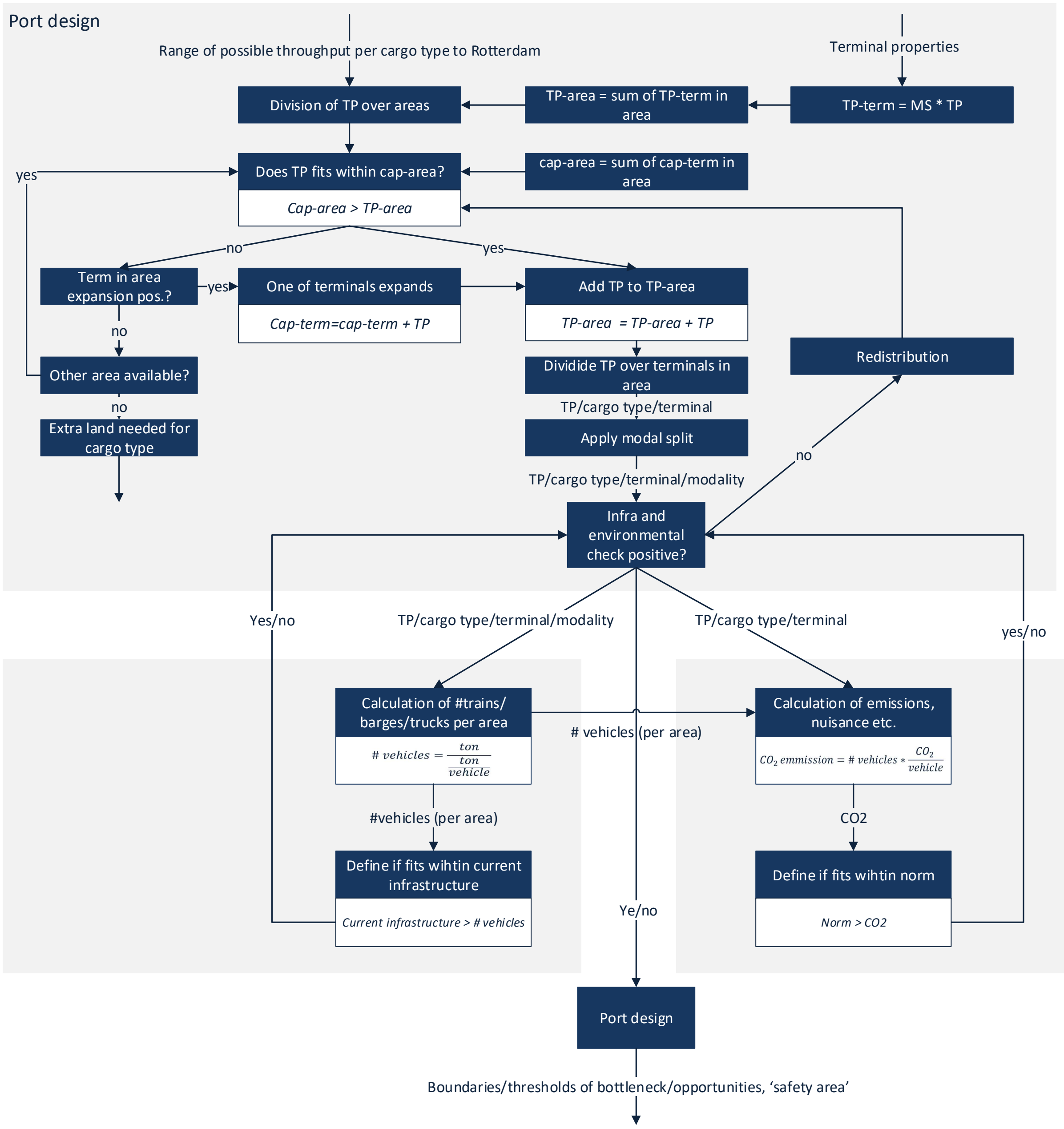


Figure 18: Satisficing Netlogo model logic

5.2.4 New project assessment

In this component, three subsystems exist: the business case calculation, business value PoRA calculation and the business case assessment. The first two elements are model components, the last element is an assessment of the output of these models by an employee of PoRA.

Business case and Port of Rotterdam business value calculation Proposed projects will be assessed based on their business case and the impact they have on the business value of PoRA. The most important variables used for the calculations are show in Table 5.

Appendix PoRA III (NPV/IRR)

Table 5: Variables for business case and business value calculation

Port specific	Case specific
Port dues	Surface of the land that will be used
Land renting tariff	Expected throughput as a result of the project
Discount rate	Initial cost
Inflation	Operational cost
Indexation	Start of the contract
	Duration of the contract

Appendix PoRA IV (diversity)

The calculations for the business cases are made in a large Excel file. A large amount of equations can be found in this document in order to calculate the IRR of the project. The person who wants to assess the profitability of a new project needs to fill in the case specific data and define whether the port specific data deviates or not.

Project assessment The project assessment element is implemented in the same manner as the social process component. This implementation will be discussed in the next paragraph.

Operational implementation (software implementation)

To meet the requirement of using existing models, in the ideal situation the existing Excel file would be coupled to the market share model. Due to time limitations, this coupling is not performed. Instead, a simplified version of the Excel file is implemented in a Python model. Because the Excel file contains a large variety of variables, for the sake simplifying the process, it is decided to not include all variables. Together with a respondent of the financial department it is determined which variables are most important to include in the Python model and in what way the IRR will be calculated, so that the Python model represents the same dynamics as the existing Excel file. Some assumptions are made:

- o port dues are equal for all companies (xx€/ton (Port of Rotterdam Authority, 2016a)
- o land renting tariff is equal for all companies (xx€/m^2)
- o inflation and indexation are not included in the model.

Appendix PoRA V (prices)

5.2.5 Social process

When performing both the project assessment and the assessment of port designs, PoRA evaluates the outcomes of the other components: the output of the port design component and the output of the market share model. In the case of the 'project assessment', the profitability of a new project and the impact on the business value will be assessed. In the second case, the port designs will be assessed. However, 'the' future does not exists, which means that based on one single outcome of the components PoRA cannot make reliable statements about the output of the model. As mentioned in Chapter 2Chapter 2:, one way to explore the different levels of uncertainty and future scenarios using the model ecosystem is EMA. EMA will therefore be applied in these elements. In this way PoRA can assess the projects and port designs under a wide range of different scenarios.

Operational implementation (software implementation)

In order to apply EMA, one needs to define which factors are the uncertain factors one wants to analyse. These factors are defined as the 'model uncertainties'. In this case the model uncertainties are:

- o growth factor GDP (growth factor energy demand)
- o uncertainties regarding the path of the energy transition
    - end value of energy transition (c)
    - speed of transition (a)
    - moment of transition (u)
- o growth factor share other grey energy sources
- o growth factor market share Rotterdam.

The model constants are:

- o initial energy demand
- o initial share of other grey energy sources
- o initial share of green energy
- o initial market share Rotterdam.

The EMA code can be found on the Github (Model ecosystem – EMA code.ipynb)

5.3 Coupling of the components

In the previous chapter the different components are designed and implemented in various software tools. In order to finalise the implementation of the proof of concept, the different components need to be coupled. In this chapter, the final step of the implementation of a proof of concept is performed. This final step concerns the coupling of the different model ecosystem components. First, an overview of different coupling methods and techniques is given and a suitable coupling technique is chosen. After that, the coupling tools that are used in the implementation are described. Lastly, the models of the ecosystem are coupled using the proposed techniques and tools.

5.3.1 Coupling techniques

In literature multiple coupling methods and techniques are discussed. However, no consensus is reached about the terminology. Four important terms concerning the coupling of multiple simulation models are: distributed simulation, parallel simulation, sequential simulation and co-simulation. In the following paragraph a description will be given.

Distributed simulation Distributed simulation is about the possibility of running multiple simulation models on different servers. The simulation models need to communicate in order to run the entire system properly. In some articles the emphasis of distributed simulation lies on the literal distribution of models over servers on different places (geographically distributed). However, the definition of distributed simulation that is formulated in this research is:

'The execution of a model run of a system using multiple simulation models that in theory could be run at different servers.'

This definition is based on the definition given by multiple other authors (Fujimoto, 2015; Perumalla, 2006; Trcka, Hensen, & Wijsman, 2006) That eventually these models will be executed at the same server, does not change the fact that it is a distributed simulation. The emphasis of this definition lies in the fact that the system is consists of different, individual models which all display some part of the system. One of the main reasons for applying distributed simulation is to use separate simulation models (federates) to form one system (federation) (Trcka et al., 2006).

Parallel simulation and sequential simulation Parallel simulation concerns the fact of how the simulation models are run. If the execution of an experiment is performed on several servers at the same time, one speaks of parallel simulation. This means that multiple replications of one model are performed at the same time (Fujimoto, 2000). In sequential simulation the replications of an experiment with simulation models will be performed successively. The results of a sequential run should be the same as the results of a parallel simulation run (Perumalla, 2006).

Co-simulation Co-simulation is an approach for the joint simulation of models developed with different tools where each tool treats one part of a modular coupled problem. Intermediate results (variables, status information) are exchanged between these tools during simulation where data exchange is restricted to discrete communication points. Between these communication points the subsystems are solved independently (Bastian, Clauß, Wolf, & Schneider, 2011). Co-simulation is a method where the different components will retain their own specialized simulator to reach the most accurate result.

Contrary to what some authors state in literature, these terms all cover a different aspect of the model coupling and the one does not always exclude the other. In this proof of concept, the coupling of the different components will be a distributed co-simulation, that is run either sequential or parallel. It is a co-simulation because multiple formalisms are used. The distributed character lets the design meet the requirement of modularity. The different components can all run independently and could be replaced by other (new or existing) components. The model ecosystem will be run parallel, which means that multiple replications can be performed at the same time.

It is chosen to use a master-slave construction. The master is an element through which the components (the slaves) communicate. This master can be compared with the RTI in the HLA (Fujimoto, 2000). The master synchronizes, controls and manages the different components (Bastian et al., 2011). In this master-component communication between the models is possible and data exchange between the models takes place. Because the communication between the components takes place through the master, less coupling tools between the different components are necessary.

5.3.2 Coupling tools

Since the different components are built in different formalisms, multiple coupling tools are used. In the following paragraphs these tools will be briefly introduced.

PyNetlogo The satisficing model built in Netlogo needs to communicate with the master component in Python. This is done via the PyNetlogo, an interface between Python and Netlogo. Via this interface Netlogo commands can be passed through from the Python environment using jpype.

Pandas Pandas is a library within Python that is used to structure and analyse data. Within this research, the data structure element is used to structure the financial and physical port characteristics data which are located in Excel. Via the pandas library the Excel files are coupled to the Python master.

Def function For the coupling of Python models to the Python master, the Def function is used. The components modelled in Python are developed in such a way that they can be called via the def function.

NetLogo Csv Extension The satisficing Netlogo model needs to import the port properties from the Excel files. This is done using the Netlogo Csv Extension.

Visual Basic The Netlogo Csv Extension needs a specific type of csv file. Currently, no tool exist to construct these csv files automatically, and files need to be adjusted manually. In order to adjust these files automatically, Visual Basic is used.

5.3.3 Operational implementation of the coupling (software implementation)

The last step in the implementation of a proof of concept is the coupling of the different components. Figure 19 shows a schematic overview of how the components are coupled. The master-component is implemented in Python. The master is a set of functions which give access to the different model ecosystem components. These functions are called in a particular order.

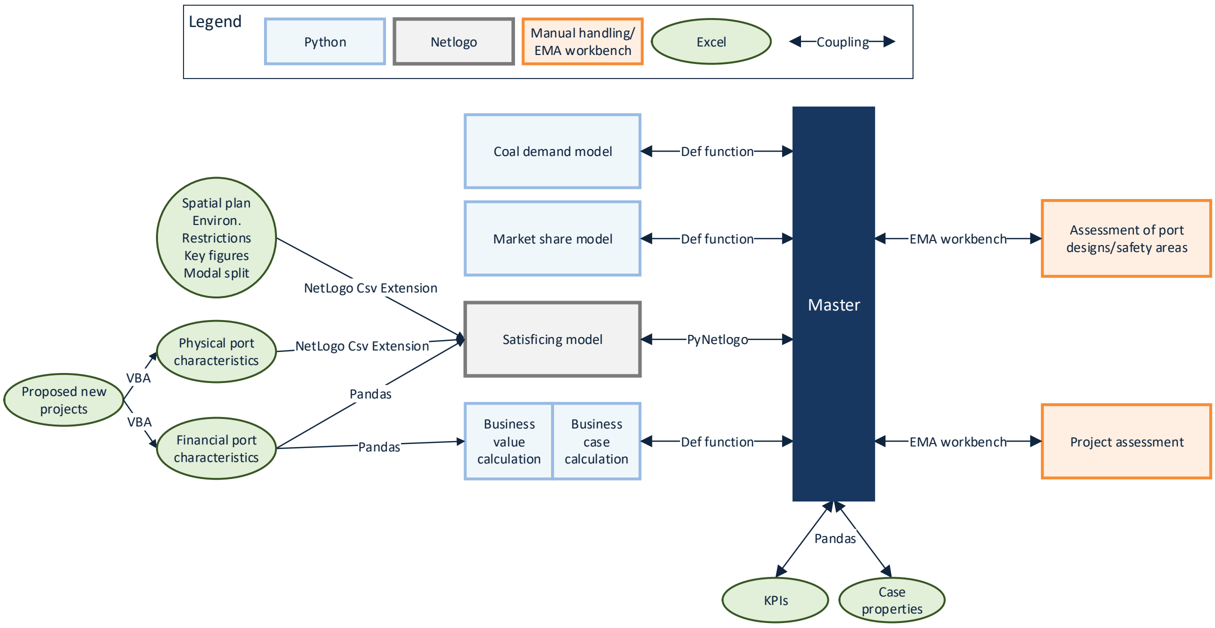


Figure 19: Visualisation of coupling

Initially, the communication between the master and the satisficing model was discrete, with communication at every time step. This means that Python and Netlogo needed to communicate in every timestep. This frequent communication had a high impact on the runtime performance. It is therefore chosen to adjust the coupling. The satisficing model constructs a list in which all variables that need to be transferred to the master are stored every time step. The satisficing model now runs one entire simulation and at the end communicates the lists with all variables recorded over the simulation. In this way the satisficing model and the master only have to communicate 2 times (at the start and at the end) of a simulation run.

In order to run the model ecosystem parallel, the MultiProcessor function from the EMA workbench is used. In order to use this module the code that was developed initially needed some adjustments.

At the start of the development of the port design component, both the environmental and infrastructural elements were built in R. Due to technical reasons these R models are replaced by Netlogo elements within the satisficing model.

During this coupling phase some challenges were encountered caused by the difference in formalisms. In Appendix F an overview of these challenges is given and it is explained how these issues are solved.

The code of the coupling of the model ecosystem components can be found on the Github (integrated_model.py).

5.4 Operational test and evaluation of the proof of concept

The evaluation consists of two parts. The first part is the technical verification. The question: "Does the model ecosystem do what I wanted it to do?' will be answered (Koen van Dam, Nikolic, & Lukszo, 2013). It will be evaluated whether the translation of the design to the implementation is done correctly. The second part concerns the validation of the model ecosystem. In this analysis it will be tested whether the models meet the requirement and if the models represent the same dynamics a the 'real world'. This second part of the evaluation phase will be based on interviews with experts and based on the comparison of the model ecosystem with the list of challenges.

5.4.1 Verification

The models of the model ecosystem are developed in an incremental way, which means that most of the verification is done during the implementation. However, this is poorly documented.

5.4.2 Validation

The validation of the model of the different components can be done in four different ways (Koen van Dam et al., 2013):

- historic replay
- face validation through expert consultation
- literature validation
- model replication.

Within this research the second option, face validation through expert consultation is the most suitable method.

Satisficing model The satisficing model is validated together with an expert from PoRA who currently manages the OPM model. The mechanisms and processes within the model are discussed, as well as the model outcomes. The model outcomes are compared to the outcomes produced by the OPM model. Since the objective of the research is to develop a proof of concept, it is not necessary to obtain the exact same outcomes of the OPM. What is of most importance is that the dynamics presented by this model match the dynamics of the OPM. Together with the employee of PoRA it is concluded that the satisficing model represents the same dynamics.

Model ecosystem In Chapter 3, a list of challenges encountered by PoRA is defined. To validate the design the model ecosystem, it is checked whether the model ecosystem contributes to overcome the challenges. The result of this analysis is shown is Table 6.

Table 6: Challenges and solutions

Challenge	Characteristic of the model ecosystem to overcome the challenge
Development of qualitative scenarios	
1. Inconsistency in terminology of qualitative scenarios	The qualitative scenarios are a result of the model ecosystem, and thus only model ecosystem factors are included. This ensures consistency between the different scenarios.
2. Expert dependent	The models will be developed with multiple employees, from different departments
3. Inconsistency between the different cargo types	In the model ecosystem every cargo type will be simulated in a separate model. These models may differ in structure. However, the in- and output criteria of the models are strictly defined, which results in the fact that the models at least give the *same types of model outcomes*.
4. Mind set of calculating and getting exact right figures in scenario use	o The satisficing model shifts the OPM from exact division over terminals, to *satisficing division* over wider areas. o By applying EMA the focus shifts from calculating 'a future', to *exploring a range of plausible futures*
5. Translation of world view	This challenges is not addressed
6. Traditional method of scenario development	Scenarios are developed by applying *scenario discovery*
7. Inconsistency between qualitative and quantitative scenarios	Scenario discovery is applied, which turns it around: the qualitative scenarios are a *direct result* of the quantitative scenarios. (instead of the quantitative a result of the qualitative)
Use of Excel in qualitative scenarios	
8. Development of scenarios labour intensive	The outcome of the PRIM analysis are the restricting dimensions, the factors that are most predictive for a particular outcome. The generation of these restricting dimensions is done *automated*, by performing a PRIM analysis. These

	restricted dimension can be translated to narratives.
9. Development of scenarios error prone	See challenges 8.
10. Not all cargo types have same structure in documents	See challenge 3.
11. Different documents not linked automatically	All cargo type models will be coupled to the market share model.
12. Not updated automatically, static	This challenges is not addressed.
13. Only extreme parts of scenarios can be calculated	By applying EMA the *full range of plausible futures* can be explored.
14. Agreement about particular figures not well documented	The implementation of a *centrally managed tracking system*
15. Changes of figures not well documented	See challenge 12
OPM	
16. Liner choices are held constant	This challenges is not addressed.
17. Redistribution of TP in OPM manually	Due to the *coupling* between the infrastructure model, the environmental model and the satisficing model, the redistribution of throughput is done *automated.*
18. Redistribution of TP expert dependent	See challenge 17
19. Redistribution of TP error prone	See challenge 17
20. Redistribution of TP time consuming	See challenge 17
21. A lot of information not centrally stored, but in 'the head' of the employees	See challenge 14
22. Forecasts about tp to terminals is very exact (3 decimals), while the base data is not even exact	The satisficing model divides the throughput over the different areas, rather than divide exact throughputs over individual terminals..
23. No dynamic changes of terminals, just growth rate	This challenges is not addressed.
24. Errors with modalities	This challenges is not addressed.
25. Miscalculations due to mistake of shipbroker	This challenges is not addressed.
Port design development	
26. Manually adjusting data to obtain right input	Models are coupled, which means that the input/output data is *adjusted automated.*
27. Port design process labour intensive and time consuming	Part of the development of the port design is automated in the model ecosystem. Only the assessment of the port designs still needs to be done manually.

28. Only able to develop one future port design	By applying EMA a *wide range of future port designs* can be developed.
Port optimizer	
29. Manual handlings in Port optimizer	See challenge 27
30. Port optimizer still time consuming	See challenge 27
31. No possibility to develop wide range of port design and test them under different scenarios	By applying EMA a wide range of future port designs can be developed and tested under a *wide range of plausible scenarios*.
Environmental check	
32. Production part is left out of scope	This challenges is not addressed.
33. Difficult to match province demands	This challenges is not addressed.
Communication between departments	
34. Communication between systems of different departments is difficult	See challenge 26
35. Inefficient loops in process	The components of the model ecosystem are *coupled*, and feedback loops are *automated*.
36. No feedback from forecasts to corporate strategy	The KPIs are measured in the project assessment component.
Business case assessment of new projects 37. Currently used scenarios are not complete enough, no dynamic price taken into account	This challenges is not addressed.
Corporate strategy	
38. Missing 'we have succeeded measure'	In Appendix C the full objective tree can be found, in which new 'we have succeeded measures' are indicated. However, most of these KPIs are out of scope for this model ecosystem.
39. Not all 'we have succeeded measure' contribute to an objective	See challenge 38
40. Not all criteria are measurable	See challenge 38

It can be concluded that the model ecosystem contributes to overcome most of the challenges. Most of the challenges that are not 'solved', concern port specific content (e.g. challenge 24 and 25).

5.5 Conclusion

The objective of this chapter was to design and implement a proof of concept of the design that is developed in Chapter 4. This is done by implementing the five components, using Netlogo, Python and Excel. The coupling is implemented via a master-slave construction. In Table 6 it is shown in what way the model ecosystem contributes to the practical challenges PoRA is facing in their decision-making process. In the following chapter, this proof of concept is used to explore in what way such a model ecosystem can support PoRA in their decision-making process.

6

Uncertainties regarding the model ecosystem

As mentioned in Paragraph 1.1, PoRA is making decisions under deep uncertainty. By using a model ecosystem, new capabilities become available to explore these uncertainties. In this chapter these capabilities are analysed. This chapter, therefore, contributes to answering the second sub-question: *In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process?* This is done by applying multiple applications of Exploratory Modelling and Analysis on the proof of concept that is developed in Chapter 5. The uncertainty space is designed and explored and various possible future paths are defined. In the last paragraph four long-term scenarios are developed, using the EMA application 'scenario discovery'.

6.1 Exploratory Modelling and Analysis

When multiple models are coupled, the uncertainty in the model ecosystem (the coupled models) is not equal to the sum of the uncertainties of the components. In Figure 20 the course of the uncertainties throughout the two coupled elements of the coal demand model and the market share model are shown. Figure 20 shows that by coupling the different models the uncertainty accumulates and 'explodes'. In this example the ranges over which the uncertainties are varied, are kept small. What becomes clear is that even with a small uncertainty space the plausible future coal throughputs for Rotterdam cover a wide range. Varying the uncertainties over the full range of plausible states is a way to deal with the unknowns and unpredictability's of these uncertainties. However, when the uncertainty space is made very large, it is not possible for PoRA to analyse every individual outcome of the model ecosystem that represents a plausible future. PoRA therefore needs an alternative way of approaching the results of the model ecosystem. As mentioned before, an appropriate method is EMA. EMA enables PoRA to explore the full range of plausible futures. And obtain insights in the bandwidth of the plausible outcomes of the models given the full range of plausible futures (Kwakkel & Pruyt, 2013).

In the following paragraphs the uncertainties within the model ecosystem are analysed, by applying multiple applications of EMA. The goal of this analysis is explore the uncertainty space and show what the capabilities of EMA are to approach the uncertainties within the port area and what could be possible when a model ecosystem is developed. Because the proof of concept consists of simplified models and the content of the models is partly based on fictitious data, it is hard to say something about substantively specific outcomes. The analysis will therefore focus on what kind of insights can be gained from the model ecosystem, the essence of the possible relations between factors and how uncertainties can be treated. To make the explanation more clear, in this analysis it is assumed that the outcomes of the model are real.

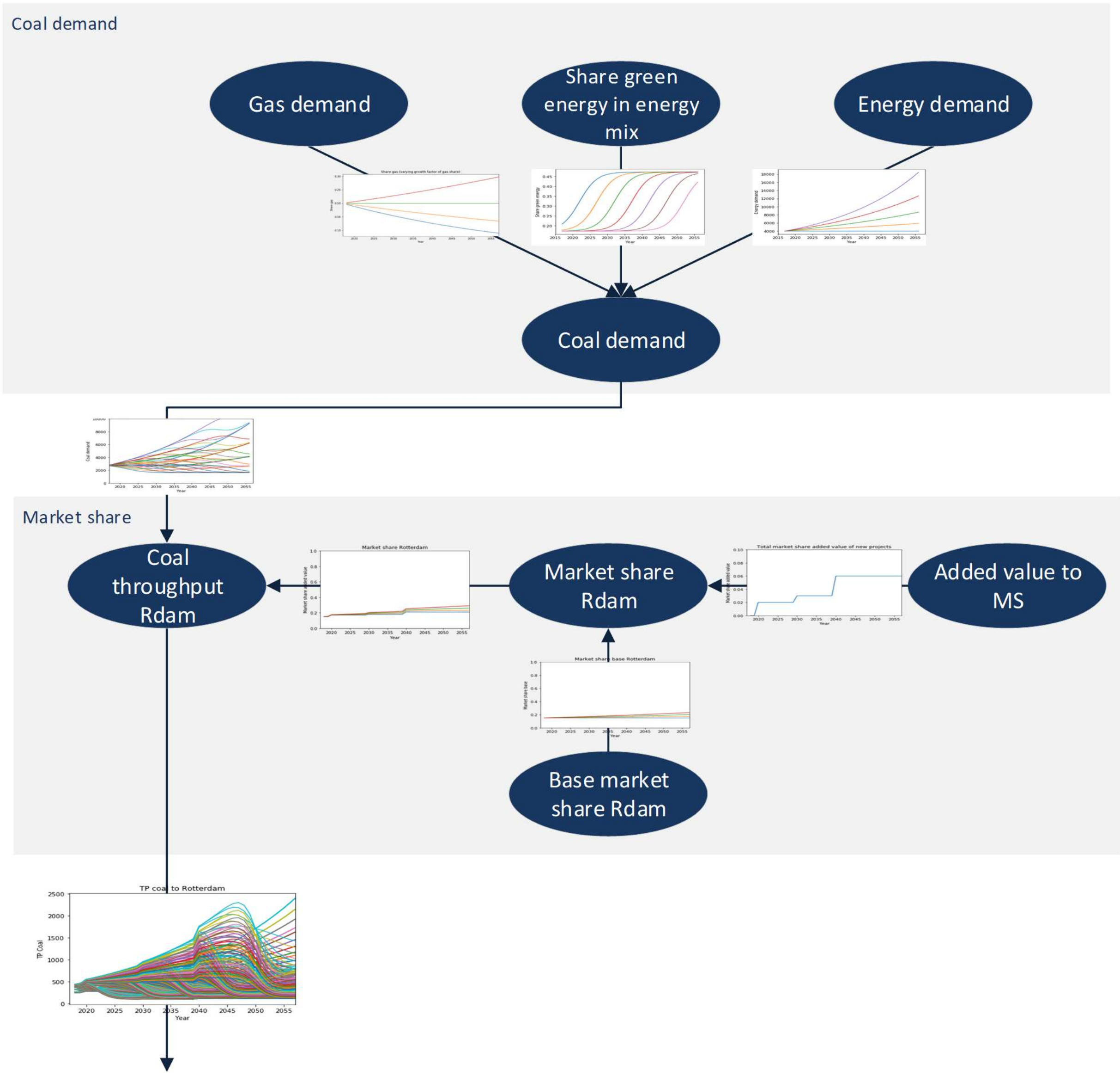


Figure 20: Uncertainty explosion in model coupling

6.2 Design and exploration of the uncertainty space and EMA environment

In this paragraph the uncertainty space and the EMA environment are defined. The following steps will be performed:

1. define output of interest
2. define the uncertainty space ranges
3. define the experimental design
4. calibration of the model ecosystem input data
5. analyse correlation between model outcomes
6. visualisation and exploration of the uncertainty space.

6.2.1 Define output of interest

Before the uncertainty space can be defined, explored and analysed, the main output of interest must be defined. In order to use the EMA workbench one needs to define the model outcomes on beforehand. However, within this model ecosystem the number of some outcomes is not known on beforehand. For example, it is not known how many terminals there will be, because in some cases terminals are closed or new terminals are constructed. This issue is solved by defining the model outcomes as lists with a varying number of elements. When the model has run, the results need to be modified in order to properly use them. This is done by creating a new result file with the specific names of the model outcomes. Through this way it is possible to obtain a (un beforehand unknown) variable number of model outputs. The additional code for performing this modification can be found on the Github (Model ecosystem - create new variables.ipynb).

The first four outputs of interests are related to the KPIs (objectives) from the corporate strategy (Chapter 3):

1. throughput without a terminal
2. throughput Rotterdam
3. occupancy
4. business value Port of Rotterdam Authority.

There are also three outputs of interests which are not related to the corporate strategy, but are needed in order to assess the profitability of new projects:

5. denied throughput due to infrastructural capacity
6. business case terminal
7. NPV.

The main model outputs are explained in the following subparagraphs.

Throughput without a terminal The first objective related to coal is: *'Rotterdam nr1 bunker location in Europe for all fuels'*, shown in Figure 21 as number 1.This is the throughput for which the port area does not have capacity. This means that this throughput would eventually go to another port, leading to a decrease of the market share of Rotterdam. This KPI will be measured in tons coal not able to enter the port area, in the model ecosystem measured through the variable *'TP_without_terminal'*.

Throughput Rotterdam The second objective related to the coal throughput is: *'Volumes in dry and liquid bulk remained'*, shown in Figure 22 as number 2. This KPI will be measured in tons coal to Rotterdam, in the model ecosystem measured through the variable *'coal_throughput_Rdam'*.

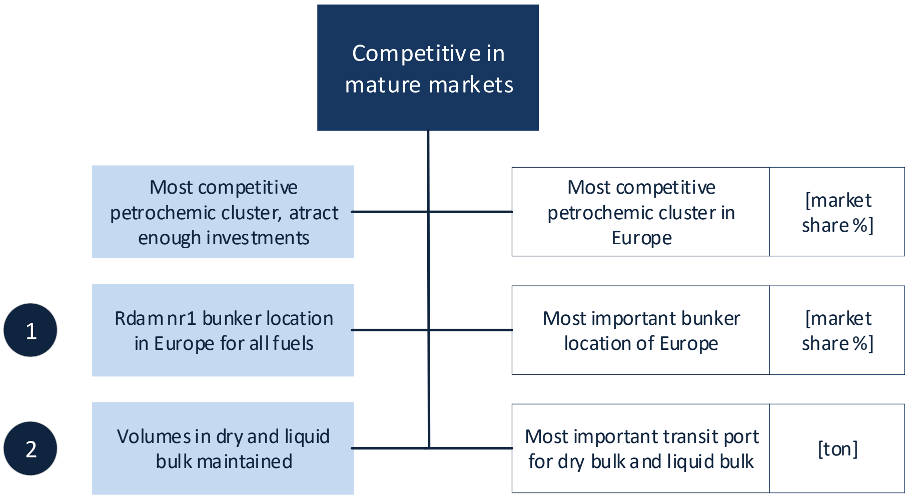


Figure 21: Objective 'Competitive in mature markets'

Occupancy One of the objectives related to the performance of the terminals is: *'Increased productivity of terminals and chemical industry'*, shown in Figure 23 as number 3. This KPI will be measured through the occupancy, which is the percentage of used capacity of the terminals, in the model ecosystem measured through the variables *'terminal_occupancy'*, *'area_occupancy'* and *'mean_area_occupancy'*. The mean occupancy of the areas is a measure for PoRA to assess the overall performance of all terminals in the port area. The higher the mean occupancy of the areas, the better the ratio of capacity/throughput, the less capacity is unused and the higher the productivity of the terminals is. If the mean occupancy is low, this could mean that a lot of terminals have unused capacity and the productivity of the terminals will be low. This means that this land could have been devoted to another cargo type, in order to increase the productivity of the terminals and contribute to the efficient use of land within the port area.

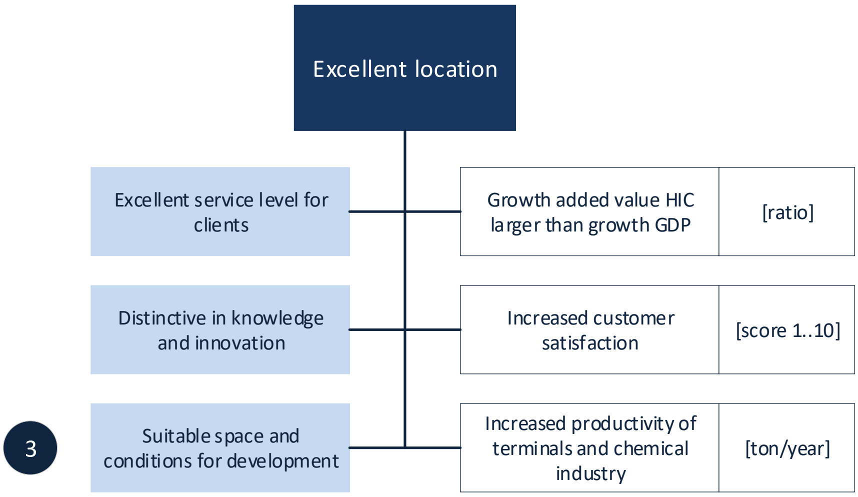


Figure 22: Objective 'Excellent location'

Business value Port of Rotterdam Authority The last objective that will be measured and assessed with the model ecosystem is: *'Maintain stable financial position and grow to A-rating'*, shown in Figure 23 as number 4. This KPI will be measured through the business value of PoRA, which is a financial indication for the value of PoRA, in the model ecosystem measured through *'business_value_pora'*.

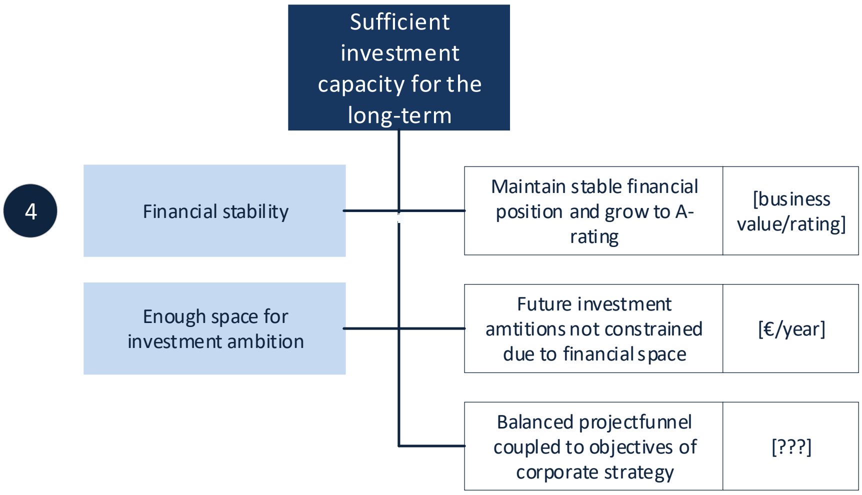


Figure 23: Objective 'Sufficient investment capacity for the long-term

Denied throughput due to infrastructure capacity This output of the model is a variable through which infrastructural bottlenecks can be ascertained. If throughput is assigned to a particular terminal, but the terminal does not have enough infrastructural capacity to process this throughput, this throughput will be defined as denied throughput. In the model ecosystem this assessment criteria is measured through the variables *'terminal_denied_infra_cap'* and *'area_denied_infra_cap'*.

Business case terminal This output of the model is a variable through which the profitability of a new project (in this case a project of land issue) can be assessed. In the model ecosystem this assessment criteria is measured through the variable *'business_case_terminal'*.

NPV This output of the model is a variable through which the profitability of a new infrastructure project can be assessed. In the model ecosystem this assessment criteria is measured through the variable *'NPV'*.

6.2.2 Define the uncertainty space

As mentioned in Paragraph 6.1, the full uncertainty space will be explored. In order to obtain plausible futures, the boundaries of the ranges of the uncertainties and the initial values of the model constants need to be defined. When a model ecosystem will be developed by PoRA, the determination of these values will be done by PoRA. This is a social process in which experts from PoRA need to agree upon which ranges of uncertainties they consider plausible. Within this research the uncertainty space will be defined based on statements about these uncertainties found in literature. The upper and lower limits of the uncertainty range are shown in Table 7. The model constants are based on the current values and are shown in Table 8. Some of these values are explained in more detail.

Table 7: Upper and lower limits uncertainty ranges

Uncertainty	Lower limit	Upper limit
Growth factor energy demand	-0.6%	1.3%
End value of energy transition (c)	3%	73.3%
Speed of transition (a)	0	0.2
Moment of transition (u)	0	38
Growth factor other grey energy sources	-1.5%	1.5%

Table 8: Values of model constants

Model cofnstant	Initial value	Model constant
Initial energy demand	240.000.000 ton	Initial energy demand
Initial share other grey energy sources	54.0% (European Union, 2015)	Initial share other grey energy sources
Initial share of green energy	26.7% (European Union, 2015)	Initial share of green energy
Initial market share Rotterdam	37.6% (Port of Rotterdam Authority, 2016b)	Initial market share Rotterdam

Growth factor energy demand The Energy Information Administration estimates an energy demand in 2040 of 30% more compared to the current energy demand (EIA, 2016). Distributed over 23 years this would lead to an average growth of 1.3% per year. Greenpeace suggests that, mostly due to energy efficiency improvements, the energy demand will decrease, leading to 20% less energy demand in 2050 (Turkenburg, Schöne, Metz, & Meyer, 2016). Spread over 23 year would lead to an average decrease of 0.6% per year.

End value of energy transition Greenpeace predicts that in 2050 a 100% sustainable energy production in 2050 is feasible (Greenpeace, 2015) . This would mean that a full transition would be reached, leading to an end value of the energy transition of 100% ($c = 100 - initial\ share\ of\ green\ energy$). In the Paris Agreement the objectives concerning the share of green energy are set on 30% in 2030 (United Nations, 2017), leading to a lower limit of 30% green energy in the energy mix ($c = 30 - initial\ share\ of\ green\ energy$).

Moment of transition (u) It is hard to define a strict moment of the start of the energy transition. It is, therefore, chosen to vary the start moment of the energy transition over the entire duration of the model (0 – 40).

Growth factor other grey energy sources The share of other grey energy sources consists of multiple energy sources, which all contain different uncertainties. The facing out of gas would lead to a decrease of the share of other grey energy sources while the increase of nuclear energy would lead to an increase of this share. It is mentioned that a port without any coal throughput would be possible (AD.nl, 2017). 100% of other grey energy sources is therefore the maximum. $1 - initial\ share\ other\ grey\ energy\ sources$, distributed over 40 years results in the upper limit of 1.5%.

Initial energy demand The initial energy demand is determined in such a way that the initial factors lead to a coal throughput to Rotterdam with the same order of magnitude as the current throughput to Rotterdam. The current coal throughput to Rotterdam (2016) is 28.443.000 ton (Port of Rotterdam Authority, 2016b).

6.2.3 Experimental design

With EMA the full uncertainty space will be explored. This will be done by performing a large number of experiments. The choice for the number of experiments is based on a trade-off between obtaining a large data set and the time it will take to execute the experiments. It is therefore chosen to perform 1000 experiments. Within the EMA workbench these 1000 experiments are sampled applying the Latin Hypercube Sampling over a uniform set of the uncertainty spaces.

Stochastic uncertainties Especially in the satisficing model, a high degree of stochastic uncertainty exist, which is the uncertainty caused by the probability of a particular event (Walker et al., 2003). In this satisficing model, the throughput is divided over the different terminals. The order in which the terminals are asked to bring the throughput to in a particular area is randomized. This causes the effect that in one model run throughput is brought to terminal 1 in area 1 and in the next model run the throughput is brought to terminal 2 in area 1. This stochastic uncertainty is reduced by performing a high number of replications when the experiments are performed. The variation of the mean occupancy over the number of replications is shown in Figure 24. This figure shows that from 50 replications the mean occupancy of a terminal is rather stable. It is, therefore, chosen to perform 50 replications of each experiment. This test is done by performing multiple experiments, keeping the uncertainties constant, an varying the number of replications.

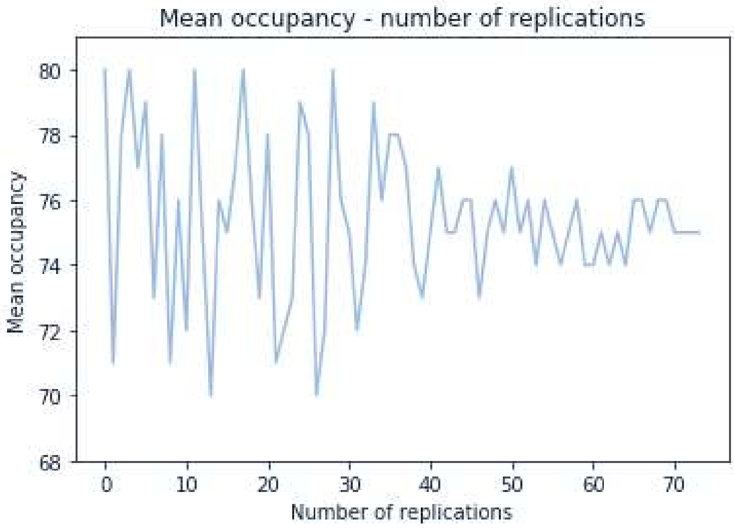


Figure 24: Number of replications

6.2.4 Calibration of model ecosystem input data

Because not all data is known or available, the input data for the model ecosystem is not always based on real numbers. Because the objective of the research is to show the possibilities of a model ecosystem the input data is adjusted in such a way that the outcomes of the model ecosystem demonstrate relevant outputs. An example is given, if the ratio of coal throughput to Rotterdam and the capacity of the terminals has a particular value, which results that in all scenarios there are no bottlenecks, there is no throughput to other ports and the occupancy of the terminals is always 100%. This is not a realistic outcome and an analysis of these outcomes does not make much sense. The calibration of the input data was an iterative process. The fact that various models are coupled complicates the calibration of data on several aspects:

- A small change of a variable in one component can have great (unexpected) impact in the outcome of another model.
- Uncertainties accumulate, which also causes that small changes in one component can have great impact on the output of another component.

- Because the components are coupled, it is sometimes not obvious at what place a variable needs to be adjusted in order to obtain the desired results.

6.2.5 Analyse correlation between model outcomes

Often in model and scenario development people assume that variables and uncertainties are correlated. They may find out in the course that the system changes and it appears that there is no (or a changed) correlation anymore. This assumption of either taken correlation into account or not, is an additional uncertainty that should be beared in mind. Within this model ecosystem system two types of correlation exist: correlation between input parameters and correlations between model outcomes. Both will be discussed in the following paragraphs.

Correlation between input parameters

The uncertain parameters within the model are not all independent, a large degree of correlation exists. In Figure 14 of Paragraph 5.2.1 the influences are unidirectional, yet in reality these relations may be bidirectional. It may also occur that correlation between the uncertainty parameters exists. This will be explained by means of an example.

Example Correlation exists between the growth factor of GDP influencing the energy demand and the share of grey energy. When GDP grows it could be that the share of green energy also grows. When people have a higher purchasing power, they tend to spend more money on renewables and energy efficiency technologies. But the growth of GDP could also cause an increase of energy demand. Which may result in the fact that the growth of GDP has both a positive and a negative effect on the growth of coal demand, which may damper the total effect of the GDP on the coal demand.

However, if you include these uncertainties independently, they will be varied across the full range in EMA (both high, is double high, or both low, so double low). If this is the case, only a limited part of the results of the analysis makes sense. And part of the results present combinations of uncertainties that will never occur in reality. A solution space that in reality cannot occur is represented, which can give a distorted view of the results. These correlations can result in rough under or over estimations of the results. In Figure 25 all possible combinations of assumptions about the uncertainties are shown. If the correlation would not be taken into account, all model outcomes would be plausible (regarding these two uncertainties). In Figure 26 it is shown that there may be a correlation between the energy demand and the share of green energy. This results in the fact that not all combinations of uncertainty assumptions may lead to realistic results. The orange shaded areas show combinations of uncertainty assumption that are not realistic and which may result in a solution space that in reality may not occur. De model outputs that correspond with the inputs in the orange shaded areas, should not be taken into account.

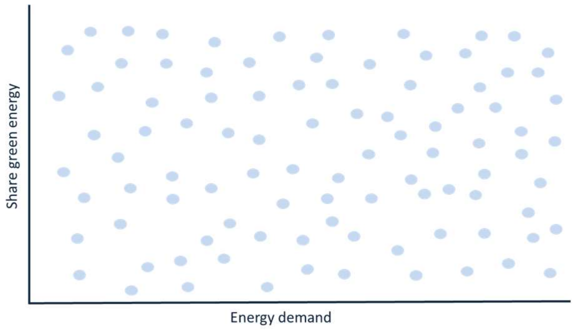


Figure 25: Full input space

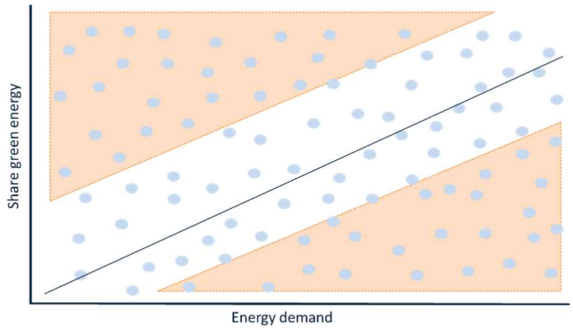


Figure 26: Unrealistic input space marked

These correlations between input parameters are not taken into account up front, but will be taken into account during the interpretation of the results. The sampling will be performed uncorrelated and during the analysis, the interpretation of the results, there will be reflected on considerations about correlations.

Correlation between model outcomes

Within the model ecosystem multiple relations exist between the variables in the model. When these relations cause correlation between particular model outcomes, this can cause misinterpretations. For PoRA it is of importance to find out what causes this correlation. Does x influence y, or the other way around, or may there be another underlying factor influences both factors. It is of importance to know if the relation between the factors is causal, or that the factors are correlated. There is no standard theory that proofs the existence of causality, but in some cases this causal relation may be clear because the relation can be justified. An example will clarify this.

Example The model ecosystem consists of multiple simple simulation models. Because the relations between these factors are simplified, some obvious causal relations exist within the model ecosystem. In the model ecosystem the business value of PoRA consists of the income gained from throughput and land renting. No other costs, income or other business are taken into account yet. Therefore, if the throughput processed by Rotterdam increases, the business value of PoRA increases. This is a causal relation, shown in Figure 27.

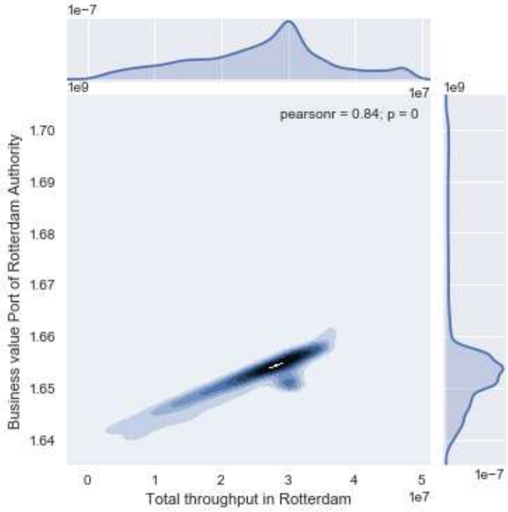


Figure 27: Causal relation between throughput and business value

Correlation between model outcomes can ask for a different strategy of PoRA. When two particular outcomes are (positively) correlated, and PoRA wants one of the two outcomes to decrease, and the other to increase, PoRA needs a strategy or a method that reduces this correlation. When a causal relations exists between these factors, it will be hard for PoRA to find a strategy that reduces one and increases the other.

A strong correlation exists between the model outcomes (Appendix G). This is partly caused by the fact that only a limited number of factors is included in the model. Because of this the relations between factors are more direct, compared to a model in which many factors are included and where factors are more interrelated and interconnected.

6.2.6 Distribution of uncertainties

With EMA it is assumed that all uncertainties are deep uncertainties. That is to say: 'we cannot say anything about the distribution of the uncertainty'. EMA analyses the impact of the uncertainties on the system without taking the probability of an outcome into account. This is done by systematically map all combinations of assumptions about uncertainties. Therefore, in the EMA workbench the uncertainty parameters are sampled from a uniform distribution. However, in reality not all uncertainties have a uniform distribution and it is not true that the distribution of uncertainties is completely unknown. The thought behind EMA is to simulate all possible combinations of uncertainty assumptions, and afterwards define which combinations are considered plausible and realistic. This will be explained by means of an example.

Example The NPV of a new terminal is calculated over a wide range of scenarios. The result of one of the analysis is shown in Figure 28. This figure shows the results of possible NPVs under the condition of possible futures. The figures does not make any statements about the probability of one of these possible futures. At first sight, the investment looks like a positive investment because the NPV is more often than not positive. However, the knowledge about the distribution of the share of green energy and the growth factor of GDP could change this image.

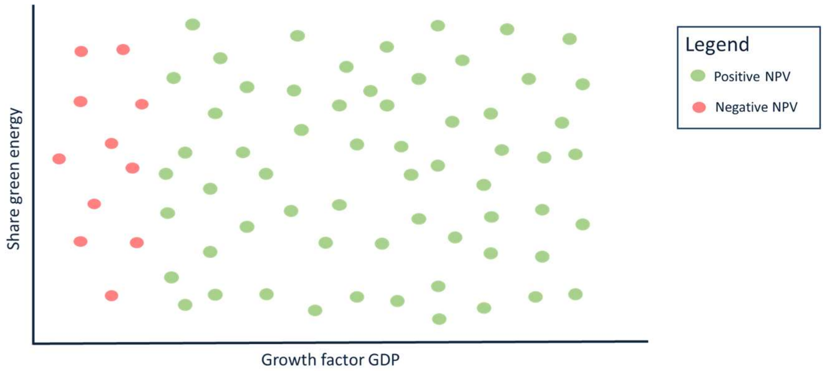
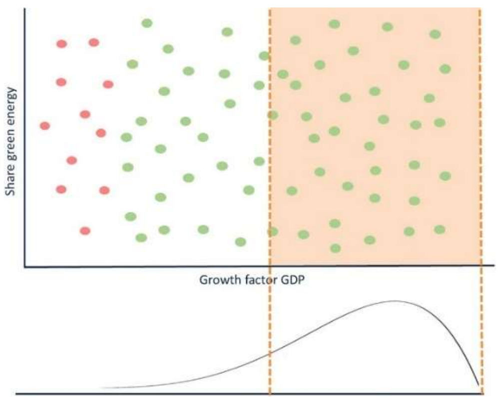


Figure 28: NPV of a new terminal

When the impact and consequences of the uncertainties are defined, it is for PoRA to determine whether they decide to give a go to the investment. PoRA itself needs to determine what they think about the probabilities. If PoRA states that the distribution of the growth factor of GDP has the form as in Figure 29, PoRA will take a positive decision about the investment in the project. If they think the distribution of the growth factor of GDP is like Figure 30, than they will probably take a negative decision about the investment of the project. What becomes clear is that by using EMA the focus should shift from predicting and analysing the distribution of uncertainties on beforehand, to first analyse the impact of possible combinations of uncertainties and afterwards assess the probability of the combinations of uncertainties.



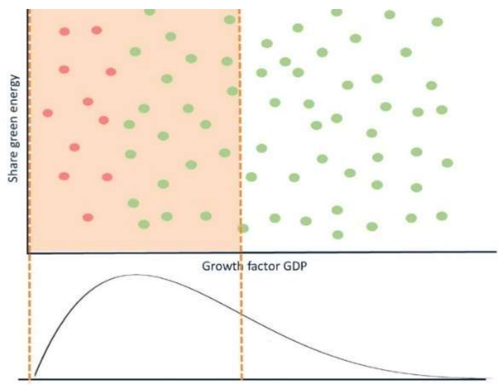


Figure 29: NPV of a new terminal II

Figure 30: NPV of a new terminal III

This means that even though a model ecosystem will be used, the assessment of the output of the model ecosystem always contains human interference. This non-uniform distribution of uncertainties should be taken into account during the interpretation of the results of the model ecosystem.

6.2.7 Visualisation and exploration of the uncertainty space

Several ways to present the uncertainty space for the model outcomes exist. In the following figures three alternative ways are shown for the model outcome 'mean occupancy of all areas'. In the first figure the blue area in the graphs represents the range of all plausible outcomes, the uncertainty space. The blue line represents the median, the green line the first quartile and the red line the third quartile. In the third figure the same results are presented with boxplots. The last figure represents the full range of plausible outcomes and 10 individual experiments are shown, accompanied by a violin density plot in which the density of the end values of the different experiments is shown.

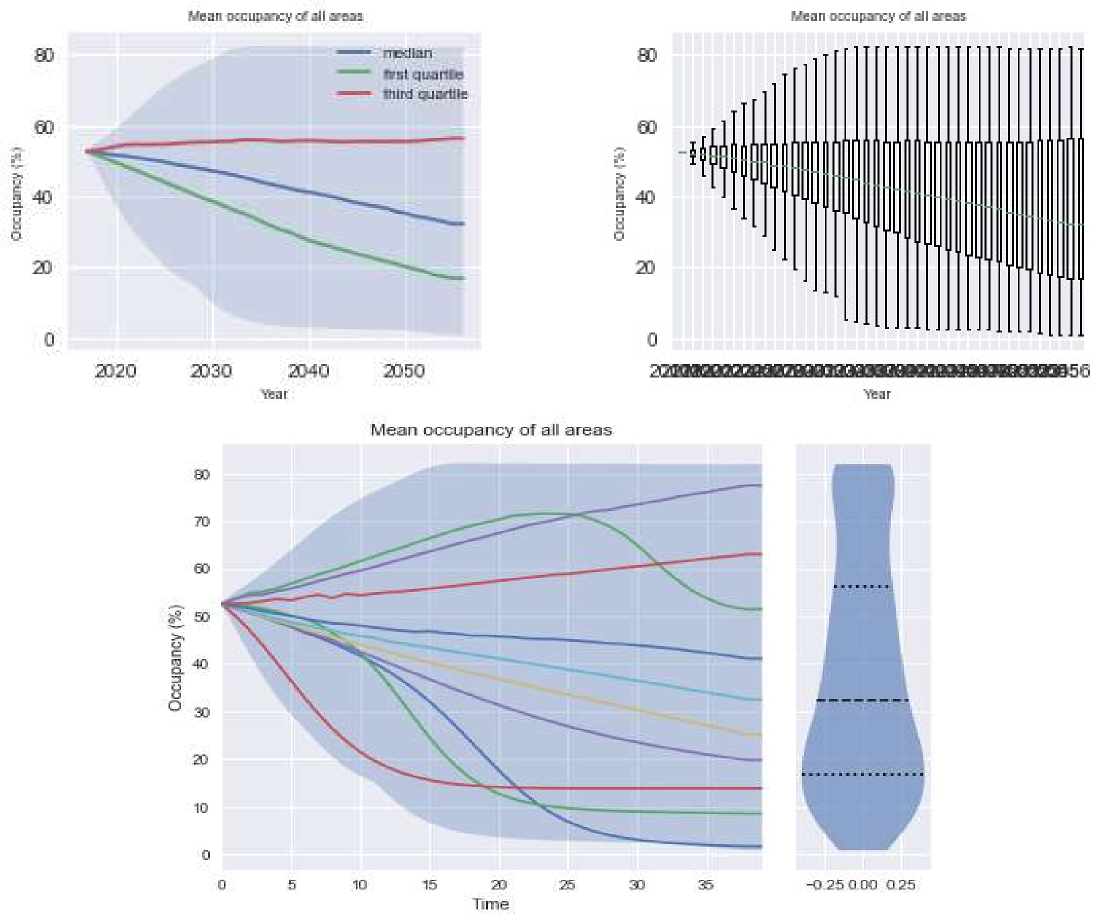


Figure 31: Visualisation uncertainty space - mean occupancy of all areas

The conclusion that can be drawn from these figures is that the uncertainty space of this model outcome, given the full range of uncertainties, is very large. This is consistent with the existence of deep uncertainty within the system of the port area. A second observation is that the range of model outcomes gets wider further in time. This is caused by the fact that the uncertainties accumulate over time, which make the far future even more unpredictable than the near future. The first two figures however, could be misleading. From the first 2 figures, the paths appear to be monotone, that the curves are monotone: the curve rises or decreases, but does not change direction. However, in the third figure it becomes clear that this is not the case. An outcome within a specific experiment can be in the first quartile at the first 10 timesteps, but changes to the third quartile for the following timesteps. In the first two graphs this connection between the different outcomes over time is lost. For PoRA it is important to know what types of paths can be expected, because a different type of path asks for a different approach. Two types of paths are defined: the monotone paths and the non-monotone paths.

Monotone path When the path is monotone, the path either increases or decreases over time. Due to the deep uncertainty it is hard to predict how much growth or decline there will be, but for PoRA this will be less 'dangerous'. If it is known on beforehand that the coal throughput will monotonically increase or decrease the coming 40 years, PoRA can respond to this by either closing terminals or attract new businesses within this cargo type.

Non-monotone path When the path is non-monotone, the path changes direction during the coming 40 years. When the path increases the first 15 years, it might seem that everything goes well, but suddenly it turns around. Because the decisions made by PoRA are often characterised by their large size and long duration and often associated with high costs, it is not possible for PoRA to attract new customers the first five years and change their strategy the next 5 years. Therefore, it is important to know when it paths fluctuate, which underlying uncertainties cause these fluctuations and how PoRA can intervene to be prepared for these fluctuations.

For PoRA it is therefore of great importance to know which subspaces provide non-monotone paths. They need to know how stable these twists are, do these fluctuations only occur with a very specific combination of uncertainty parameters, or with a wide range of parameters. How likely is it that these combinations of uncertainty parameters occur and how stable are these subspaces. And how plausible are these combinations of uncertainty parameters. Because then you should really take these paths into account. On the other hand, PoRA also needs to know which uncertainty subspaces provide non-monotone paths.

6.3 Development of long-term strategic scenarios

In Chapter 3Chapter 3: it is mentioned that PoRA uses their long-term scenarios in order to communicate with internal and external stakeholders. It is mentioned that in the current situation PoRA constructs five long-term scenarios which all demonstrate 'a possible future'. These scenarios are developed statically and based on the extreme values of the four main drivers defined by PoRA (Appendix B). In this method, qualitative scenarios (developed by experts) are translated to quantitative scenarios. By constructing the scenarios in this traditional way, not all possible combinations of uncertainties can be taken into account. And because uncertain factors are grouped on beforehand, some interesting possible combinations of uncertainties may be lost. An appropriate application of EMA to develop scenarios is scenario discovery, which creates the ability to turn it around and to translate quantitative scenarios, to qualitative scenarios (Kwakkel & Jaxa-Rozen, 2016). Scenario discovery enables the fact to take all ranges of uncertainties into account. With this method, the outcomes of a model are more seen as 'a possible future', rather than a hard prediction (Bryant & Lempert, 2009). When scenario discovery is applied, several subspaces within the uncertainty ranges will be determined. These subspaces are determined based on the impact they have on the system. These subspaces can be translated to '*communicable, internally consistent, and plausible narratives*' (Greeven et al., 2016).

The Patient Rule Induction Method (PRIM) is an often used algorithm to perform scenario discovery. '*PRIM identifies regions in the model input space that are highly predictive of producing model outcomes that are of interest*' (Kwakkel & Jaxa-Rozen, 2016). PRIM divides the uncertainty space in boxes and searches for the box with the highest density and the highest coverage. The coverage means: of all cases of interest, how many are situated within this box. The density means: of all cases in the box, how many are of interest. The outcome is a number of restricted dimensions, indicated with a range. These restricted dimensions are the uncertainties that are most predictive for the outcome of interest. An example of such an outcome is shown in Figure 32. In this case there are three restricted dimensions: growth of the market share, growth of other grey energy sources and the growth of the energy demand. The range of the uncertainty subspaces that is predictive for a particular model outcomes is indicated with the blue lines.

Figure 32: Example PRIM result

Classification rule

The first step in PRIM is to define the classification rule. The classification rule determines which outcomes are of interest. In this way multiple narratives can be developed, which all cover a particular set of outcomes. These narratives can be developed from various point of views. Some general examples are given (not only examples within this proof of concept, applied to the coal case):

- increasing/decreasing throughput for Rotterdam
- low/high share of conventional cargo types
- low/high share of sustainable cargo types and sustainable production
- low/high market share of Rotterdam.

The classification rule for this case will be determined from the point of view of the land issue projects for coal terminals. One of the main variables in these projects is the coal throughput to Rotterdam, and this will thus be the outcome that will be used for the development of the narratives (scenarios). The different types of paths defined in the previous paragraph will be used to define the classification rule. Four types of paths are identified:

1. monotonically increasing
2. monotonically decreasing
3. non-monotone, starting with a decrease
4. non-monotone , starting with an increase.

The classification rule through which these different paths of the coal throughput to Rotterdam can be found, is based on the ratio between the total variation of the path and the absolute growth of the path. In the following figures, an example of every path and the corresponding ratio are shown.

Figure 33 shows the path of experiment 27, this path is monotone. The absolute growth of the path is 268712383 and the total variation of the path is also 6871238.

$$ratio = \frac{total\ variation}{absolute\ growth} = 1$$

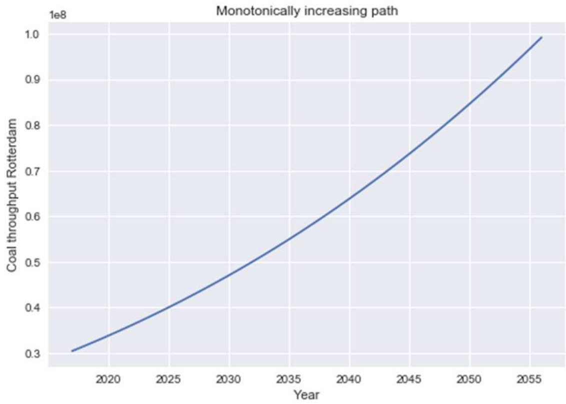


Figure 33: Coal throughput Rotterdam – monotonically increasing

Figure 34 shows the path of experiment 46, this path is monotone. The absolute growth of the path is 14407718 and the total variation of the path is also 14407718.

$$ratio = \frac{total\ variation}{absolute\ growth} = 1$$

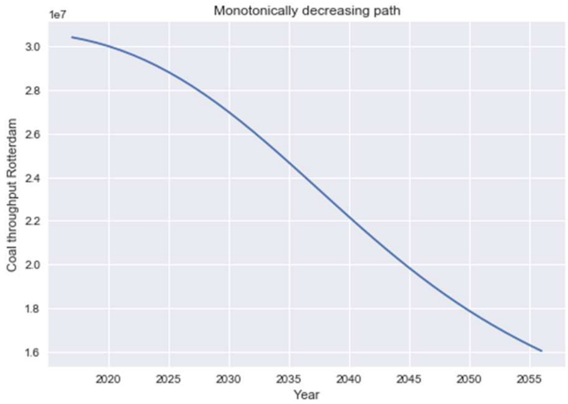


Figure 34: Coal throughput Rotterdam – monotonically decreasing

Figure 35 shows the path of experiment 893, this path is non-monotone. The absolute growth of the path is 4543094. The total variation of the path is 8812396.

$$ratio = \frac{total\ variation}{absolute\ growth} = 1.94$$

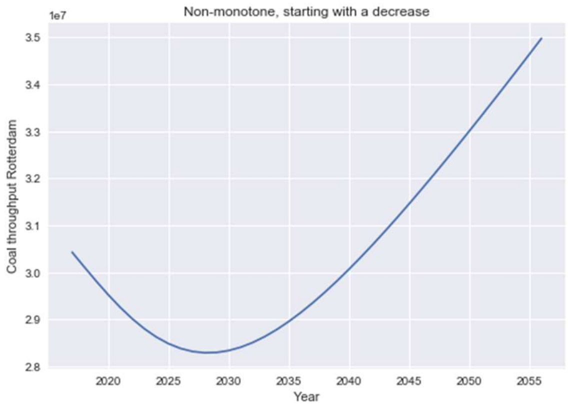


Figure 35: Coal throughput Rotterdam – non-monotone

Figure 36 shows the path of experiment 22, this path is non-monotone. The absolute growth of the path is 722018. The total variation of the path is 8878903.

$$ratio = \frac{total\ variation}{absolute\ growth} = 12.29$$

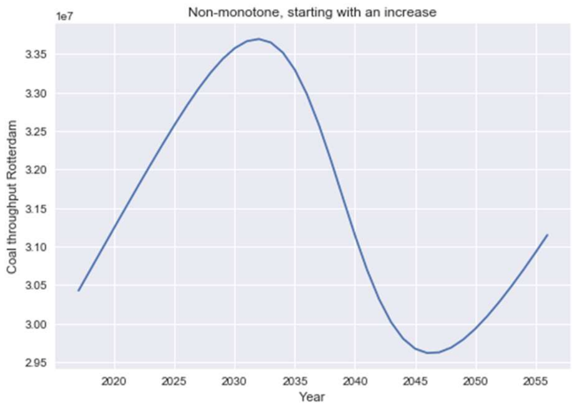


Figure 36: Coal throughput Rotterdam – non-monotone

For every type of path a different classification rule exists, these classification rules, the implementation and outcomes of this PRIM analysis with these particular classification rules can be found in Appendix H. Logical indexing is used to apply this classification rule. Based on the outcomes of this PRIM analysis, the following four narratives are constructed.

Narrative 1 In this scenario the coal throughput for Rotterdam monotonically increases. This means that PoRA needs to make a strategy which ensures that new businesses for this cargo type are attracted. New terminals should be constructed or existing terminals need to expand. This is caused by an increase of the share of coal throughput in the grey energy mix. The energy transition takes place at a low pace, which causes that the share of green energy is not increasing that fast, leading to more demand for coal. Rotterdam is performing good compared to other ports within the HLH range, leading to an increase of market share the coming 40 years.

Narrative 2 In this scenario the coal throughput for Rotterdam monotonically decreases. The means that the current capacity of PoRA, regarding the coal cargo type, needs to decrease. Terminals need to be closed or capacity needs to decrease. Land will become available for other cargo types. This is caused by an increase of other grey energy sources. The overall market share of Rotterdam decreases, which lead to the fact that PoRA needs to focus more on the competition with other port within the HLH range.

Narrative 3 The third scenario concerns the futures where the path of coal throughput is non-monotone, and where the paths the first year decrease. This chance that this path occurs is really low, and therefore, no narrative is written for this scenario.

Narrative 4 In this scenario the coal throughput for Rotterdam is non-monotone, starting with an increase. The energy transition is not starting earlier than 2030, leading to an increase of coal demand the first years. PoRA should adjust their strategy in order to respond to this increase, e.g: attracting new business in order to meet these demands or expanding current terminals. However, due to the fact that, when the energy transition start in 10 years, it takes place at a high pace, the coal throughput is declining again. PoRA needs to be really careful that their strategy also prepares them for a decline on the longer run. The terminals that are expanded the first few years, will have a large unused capacity the last years, resulting in a decrease of the occupancy of these terminals. The market share of Rotterdam keeps increasing the coming years, just like it did the last few years. Which might provide opportunities to invest in other, upcoming cargo types.

6.4 Conclusion

One of the main challenges PoRA is facing, is the deep uncertainty under which they need to make decisions. In this chapter several methods are introduced that enable PoRA to explore the uncertainties in a more systematic way and provide them with insights into the uncertainties regarding their decision-making process. This chapter, therefore, contributes to answering the second sub-question:

In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process?

By applying different techniques of EMA on the proof of concept that is developed in Chapter 5, several insights are gained from the proof of concept. The most important feature of EMA is that a wide range of plausible futures can be explored. By exploring this wide range of plausible futures, PoRA can discover what types of future paths exists. In this research four main type of paths are defined:

1. monotonically increasing
2. monotonically decreasing
3. non-monotone, starting with a decrease
4. non-monotone , starting with an increase.

When the path is monotone, the path either increases or decreases over time. When the path is non-monotone, the path changes direction during the coming 40 years.

A second important capability of the model ecosystem together with EMA, is the development of long-term strategic scenarios. By applying scenario discovery to the model ecosystem, quantitative model outcomes can be translated to *communicable, internally consistent, and plausible narratives.*

These various techniques to analyse the results of the model ecosystem are used to discuss the impact of the model ecosystem on PoRA in a validation session.

7

Implications of a model ecosystem for the Port of Rotterdam Authority

In this chapter, the last sub-question is addressed: *How would the implementation of a system of models impact the Port of Rotterdam Authority?* This chapter starts with the explanation of the three different ways of using the model ecosystem: predictive way, explorative way and normative way. The model use is demonstrated by showing how a proposed project, concerning a new terminal, could be assessed using the model ecosystem. In the second part of this chapter, the results of validation sessions with experts from PoRA are discussed. In these validation sessions multiple aspects of the implementation of a model ecosystem within the organisation are discussed: the design of the model ecosystem, the results of the assessment of a proposed project, the added value, what is needed to implement a model ecosystem, the shift of role of employees and the results of the model ecosystem example. In the last part of this chapter, the impact of the model ecosystem on the decision-making process is analysed. Both the impact on the process and the impact on the decisions itself are addressed.

7.1 Use of model ecosystem

The model ecosystem can be used in three different ways: a predictive way, an explorative way and a normative way. In the following sub-paragraphs these three different ways will be explained.

7.1.1 Predictive way

In the predictive way the 'what-if' question will be answered. 'What if' a particular new project will be implemented. This predictive way of using the model ecosystem will be used to evaluate proposed new projects and is especially suitable for planning and investment issues (Bojeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). These new projects will be inserted in the model ecosystem and PoRA can assess these projects by evaluating the business case of these projects, the impact of these new projects on the KPIs of PoRA and evaluate whether bottlenecks or opportunities occur because of these new projects.

Model use

As mentioned in Paragraph 5.1, the scope of the research consists of three types of projects. In Table 9 information about the assessment of these projects is shown. In this table it is explained which input of the model ecosystem needs to be changed in order to assess the impact of the project and which output is relevant for this assessment.

Table 9: Model information about project assessment

Type of project	Input change in model ecosystem	Relevant output
Issue of land for terminals	Adjustment in Excel of physical port properties	Impact on KPIs and business value of PoRA
		Business case specific terminal
		Bottlenecks or opportunities from port design
Infrastructure	Adjustment of added value of market share (Python MS model)	Impact on KPI's and business value of PoRA
	Infra cap of area increases/decreases	Bottlenecks from port design
Commercial actions	Adjustment of added value of market (Python MS model)	Impact on KPI's and business value of PoRA
	Adjustment values in business value calculation model	Bottlenecks from port design

Based on the information given in Table 9 the steps that need to be performed for the predictive analysis are defined. The steps that need to be taken in order to perform this analysis are quite the same for the three types of projects. Only in case of a land issue project the second step does not have to be taken. The steps are as follows:

1. Adjust physical port properties by inserting the case properties of the specific project.
2. Determine the expected added value of market share and starting year of the project.
3. Run the model ecosystem with these new properties.
4. Evaluate and assess the impact of the specific project on KPIs and business value of PoRA.
5. Ascertain bottlenecks and opportunities caused by the specific project.
6. Make the final assessment of the project (decide whether the project will be implemented or not).

7.1.2 Explorative way

The second way to use the model ecosystem, the explorative way, is to evaluate the impact of changes in the environment on the port area. For example if new trends are discovered by PoRA, and PoRA wants to analyse the impact of these trends on the system, and they want to determine whether they should take actions or not. The question 'what can happen' will be answered.

Model use

When the impact of trends (environmental changes) is evaluated, one needs to adjust the models that determine the environment. This could for example be a modification in the coal demand model, a change in the key figures of the environmental check or adjustments in the market share model. The following steps needs to be performed:

1. Modify the coal demand model.
2. Run the model ecosystem with this new coal demand model.
3. Evaluate and assess the impact of the trend on KPIs and business value of PoRA.
4. Ascertain bottlenecks and opportunities caused by the trend.
5. Determine whether PoRA needs to change its strategy or propose new projects.

7.1.3 Normative way

In the third way, the normative way, the model ecosystem will be run and the outcomes will be evaluated in order to detect either bottlenecks or opportunities. Based on these bottlenecks and opportunities PoRA can assess whether new projects need to be initiated. In this normative use PoRA can determine what actions they should take or how they should adjust their strategy in order to reach their objectives and KPIs. Through these three manners of using the model ecosystem the impact of a change in one of the components, on the ecosystem can be assessed. At every place in the ecosystem changes can occur and these changes can have several impacts on the different components. In Figure 37 numbers are indicated in the model ecosystem. These numbers represent historical events or expected future events or environmental changes that could impact the port area.

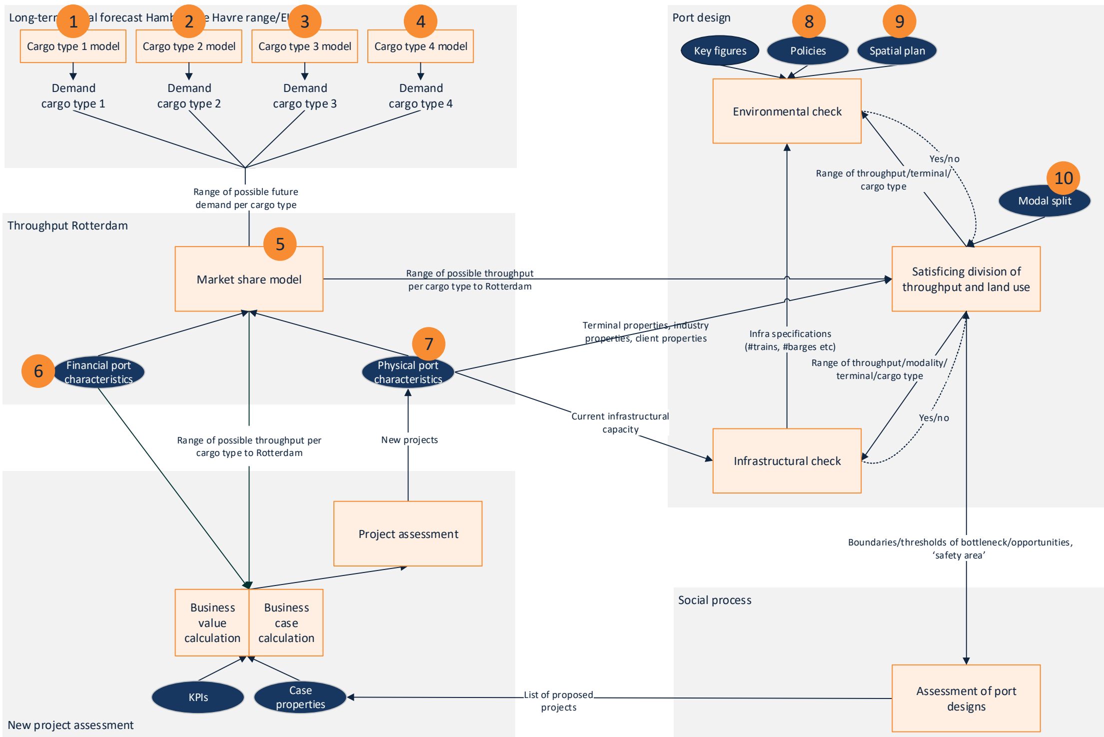


Figure 37: Events indicated in the design

The number represent the following events:

1. the Paris agreement
2. the Brexit
3. Trumps election
4. oil boycott
5. closure of powerplants in the Netherlands
6. adjustment of port dues or renting price
7. new LNG facilities
8. stricter environmental limits
9. adjustment to spatial plan of municipality
10. synchromodality, shift from truck to trains and barges.

Model use

In contrast to the assessment and explorative use of the model ecosystem, the normative use of the model ecosystem does not focus on the impact of one specific project or one specific change in the environment. Therefore the steps that need to be taken in order to perform this normative analysis differ. The steps are:

1. run the model ecosystem
2. evaluate and asses the relevant output
3. ascertain bottlenecks and opportunities
4. determine whether PoRA needs to change its strategy or propose new projects.

7.2 Example of the use of the model ecosystem

The example treated in this paragraph is about the decision of land issue for a new terminal at The Maasvlakte. The steps of the 'predictive use' need to be performed.

7.2.1 Adjust physical port properties by inserting the case properties of the specific project

This step can be performed by inserting the project properties within the Excel file of the port properties, an example is shown in Figure 38.

1. insert the type of project, in this case 'New terminal'
2. insert the case properties
3. upload the data to the physical port properties element.

New terminal	
x	5
y	1
Name	Terminal X
Area	Maasvlakte
Surface	10000
Max overslag/capacity	100000
EP (%)	0.1
Cargo type	Coal
Truck mod spl	10
Train mod spl	20
Barge mod spl	70
Truck cap	350
Train cap	200
Barge cap	600
Construction year	2025

Figure 38: Example of model use

7.2.2 Evaluate and assess the impact of the specific project on KPIs and business value of PoRA

When this step is finished, the model ecosystem can be run with the new properties. In order to assess the impact of the proposed project, the model will be run both with the current port properties and with the new properties. After the execution of the model runs, the outcomes need to be evaluated and the terminal needs to assessed. The following criteria will be assessed:

- Would the new terminal contribute to the KPI of throughput, and thus attract new throughput to the port area (Or does it just shifts throughput from other terminals within the area or within the port area)?
- Would the terminal cause infrastructural bottlenecks?
- What is the occupancy of the terminal?

Scenario discovery

To assess the new project, scenario discovery will be applied. As mentioned in Paragraph 6.3, the first step in this analysis is to define the classification rule. Based on the previous assessment criteria, the following classification rules are defined. The code of the PRIM analysis can be found on the Github (Model ecosystem - new terminal assessment.ipynb):

$$Throughput\ area_{project} > \ Throughput\ area_{current}$$

$$Throughput\ Rotterdam_{project} > \ Throughput\ Rotterdam_{current}$$

$$Occupancy\ terminals > \ 50$$

EMA the full uncertainty space is explored, sampling uncertainties from a uniform distribution, leaving the correlation out of scope. As mentioned in Chapter 6Chapter 6:, not all uncertainties are uniform distributed in reality and correlation between uncertainties exist. These characteristics of the uncertainty space are not taken into account on beforehand, but need to be taken into account during the interpretation of the results. In the following paragraph the results of the PRIM analysis will be analyses, taken these notes into account.

Results of PRIM analysis

Applying the earlier mentioned classification rule, the results show 198 cases of interests (20%). The results of the PRIM analysis are shown in Figure 39.

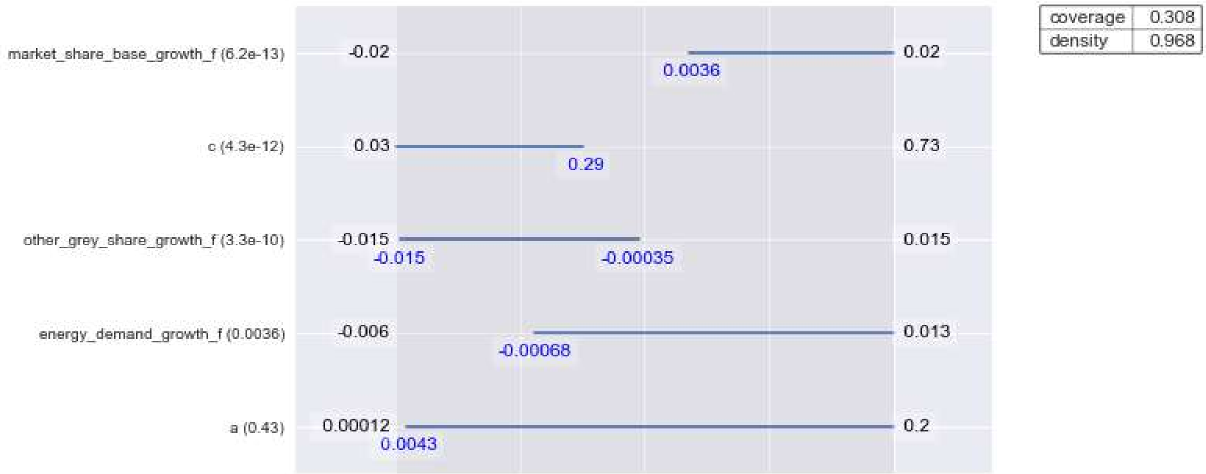


Figure 39: Results PRIM analysis (assessment new terminal)

This figure shows that there are five uncertainties that are highly predictive for a positive assessment of the project, of which four are significant. In Figure 40-Figure 43 these uncertainty subspaces are shown. The orange shaded area is the uncertainty subspace that is highly predictive for a positive outcome, regarding the new project.

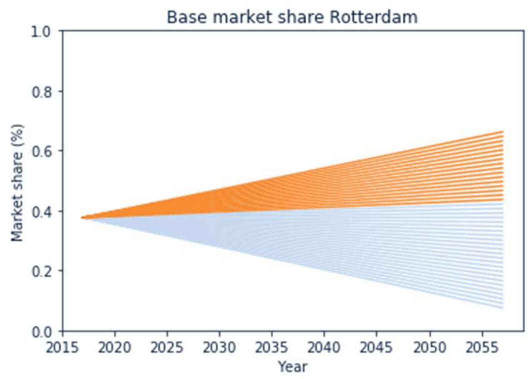


Figure 40: Base market share Rotterdam

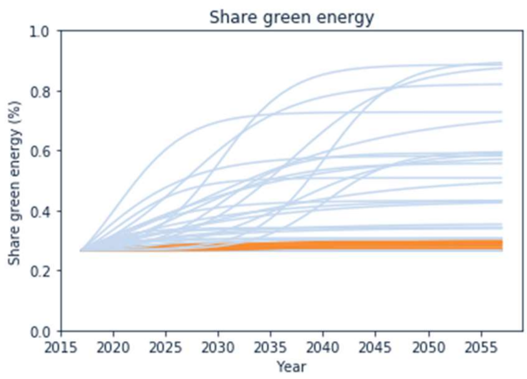


Figure 41: Share green energy

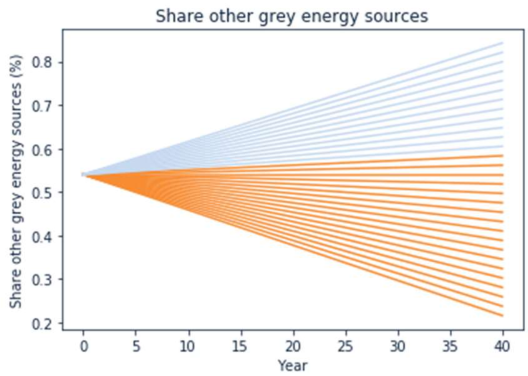


Figure 42: Share other grey energy sources

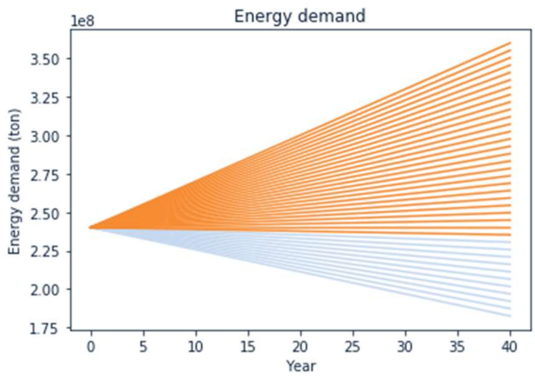


Figure 43: Energy demand

Combining these uncertainty subspaces, leads to plausible ranges of coal throughput for Rotterdam that are shown in Figure 44. The outcomes of the validation session about these results are discussed in the next paragraph.

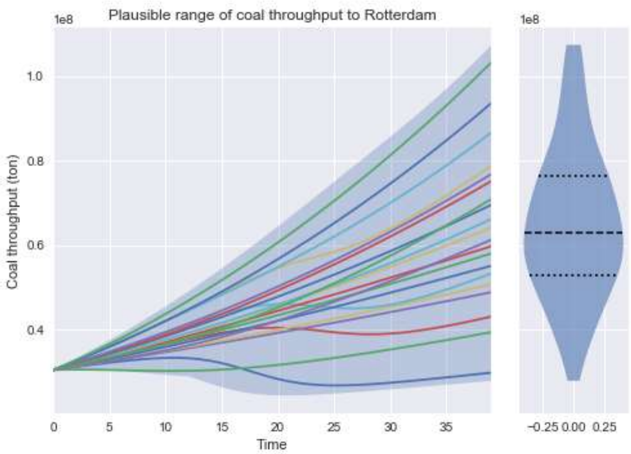


Figure 44: Plausible ranges of coal throughput for Rotterdam

7.2.3 New infrastructural project, to solve infrastructural bottlenecks

Based on the results that are obtained from the model ecosystem, PoRA could decide to propose a new project that would solve the infrastructural bottleneck that would be caused by the terminal. They need to decide what the characteristics of the new project will be:

- the type of modality: truck, train or barge
- the capacity of the new infrastructural project
- the starting year of the project
- estimation of the investment costs and operational costs of the project
- estimation of the added value of market share of the project.

When these characteristics of the proposed project are defined, PoRA can assess what the impact of this project will be on the port area. They can evaluate whether the bottlenecks caused by the new terminal can be remedied by implementing this infrastructural project. The analysis of this infrastructural project will consist of the same steps as the assessment of the terminal project.

7.3 Expert consultation about the impact of the model ecosystem on the organisation

In order to analyse the impact of a model ecosystem on PoRA, five experts from different departments are interviewed. The full interviews can be found in Appendix I. At the end, a joint validation session is held. In this paragraph the outcomes of these interviews and the validation session are be summarised and interpreted.

New capabilities of the design with respect to the current situation

The main advantage endorsed by multiple respondents is the integral approach of the model ecosystem. Because the components of the model ecosystem are linked and coupled, the focus will be more on the whole system than on the individual components[7]. Due to this integral approach, the process of translating results from different components to usable information will be faster and multiple aspects can be analysed together[8]. Added to that, the fact that models will be coupled more, and more elements will be automated, enables PoRA to include more quantitative variables, and that they are not stuck anymore to the five scenarios. This means that time will be saved while using the model ecosystem and that plans can be validated faster resulting in a faster decision-making process. Another advantage of the model ecosystem named by the respondents is that the use of systematic simulation models will give more quantitative support to decisions, and less decisions and negotiations based on gut-feeling[9].

Improvements and broadening suggestions

The first improvement named by the respondents is that this design is rather throughput driven. However, not everything in the port area is throughput driven. The suggestion was made to include

[7] Translated from: Dat je dat niet stap voor stap hoeft te doen en alleen naar je eigen gebiedje kijkt.
[8] Translated from: Het is nu steeds of/of, of milieu, of infra, in dit systeem kan je en/en doen
[9] Translated from: Geen Excel om lange termijn ramingen te doen, gebaseerd op onderbuik gevoel

non-throughput-driven businesses within the model, like distribution, industry or off-shore. The same counts for not yet existing cargo types, for example hydrogen. In the current process a distinction is made between long-term forecasts and medium term forecasts. In the medium term forecasts the changes within the port area that are known on beforehand are taken into account[10]. In this design future changes that are certain cannot be implemented.

Feasibility of the development and implementation of a model ecosystem

All respondents agree upon the fact that the development and implementation of a model ecosystem is feasible. Despite that, they are all questioning whén this will happen. Comparisons are made to the port optimizer, which is a first step in the direction of a more integrated model ecosystem. However, they also indicate that the development of the port optimizer is already a long lasting process itself, let alone the development of a fully integrated model ecosystem. The expectations are, therefore, that a full implementation will take many years.

Mind-set, money, or knowledge?

Mind-set! Is the first answer all respondents give and indicate as the most import factor needed for the realisation. If the mind-set of (mostly) the board of directors will change, money and knowledge will follow naturally[11]. By one of the respondents knowledge is indicated as a limiting factor, because not everybody has an understanding of what it is and what is possible[12].

First steps towards the implementation of a model ecosystem

What is needed? The simple answer is: good models and people who understand these models

In order to make good models, investments are needed to build these models and obtain the right data. And if the models need to be implemented within the organisation, the people who are making the decisions need to be taken on this journey, of thinking this way. They need to understand that the model ecosystem is an addition to their job, and not a replacement. An addition that eventually improves their work. Because here the resistance can occur, if people will have the feeling that they are replaced and overruled by a model.

A clear and solid plan is needed to obtain a 'go' for the investment decision about the model ecosystem. And it starts with people who can make and understand the models and, above all, explain and transfer the knowledge. With only somebody who can make good models, PoRA will have models that nobody understands. On the other hand, only people who support this change, and understand the added value, will not bring PoRA any further either. PoRA needs 'and and'.

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[10] Tranlatated from: Klant informatie, bepaalde klant gaat ineens biomassa bijstoken, dus meer vraag. Maar je weet deze vraag zeker, is geen onzekerheid meer

[11] Translated from: Kennis kun je gewoon 'kopen'

[12] Translated from: Eerder beperkend, omdat mensen niet begrijpen dat het kan

But first, PoRA needs to understand that there is a need for models, as an organisation. They need to understand the latent need for these types of models to improve the existing process. First understand how it works, and then it can be done.

A proof of concept, or other simple models could be used to make the added value of a model ecosystem more visible and more tangible. It can demonstrate what a model can actually do, otherwise the term 'model ecosystem' remains vague. PoRA should watch for, that it remains with only a strategy: 'Our strategy is to build models'. Nice, but what are we going to do? How does that work? This proof of concept and the first (simple) models could help in this process. It should be clear not only what 'PoRA' should do, but what is expected from the employees, how is their job going to change? What are théy going to do. This will also contribute to reducing the resistance of employees.

Shift of role of PoRA employees

Most respondents agree upon the fact that despite the introduction of more automated simulation tools, the human intervention within a model ecosystem will remain very import for several aspects:

- The development, adjustment, improvement and maintenance of the models. The content of the models need to be defined by the employees.
- The quality of the data used within the model ecosystem needs to be controlled and updated.

Multiple respondents expect a shift in their role, from generating data (from the OPM, development of port design), to the assessment model ecosystem outcomes and results ('expert judgement'). One respondent emphasizes the role of humans within the use of a model ecosystem, data needs to be verified and validated, and model outcomes are not unambiguously, one needs to have enough knowledge about the content in order to interpret the outcomes of the model ecosystem in the right way.

Translation of coal to a generic model

The main conclusion is that the main translation to a generic model concerns the long-term forecast model. In this model every cargo type shows different developments and is determined by different factors and uncertainties. In the other components key figures may differ for the different cargo types, but the approach remains the same. The types of decisions made for the different cargo also have the same characteristics. One respondent even states that the environmental check is almost independent from the cargo type, whether a ship is carrying coal or some other cargo type does not change the emissions it generates. Maybe some slightly different key figures, but again, the approach remains the same for the different cargo types.

Other implications for PoRA

If a model ecosystem is implemented at PoRA, this will impact the organisation on multiple aspects. One is that PoRA will be more objectively looking at what they want to achieve or want to do with the port area. This also means that there will no longer be 'the coal department' and 'the container department' and 'the oil department', all of which aim is to get as much coal, containers and oil as possible. Currently, all those separate departments are all looking at their own case. But the model ecosystem enables an integral trade-off between different cargo types. It will support decision about where to focus on and to which cargo type particular land will be devoted. And these decisions can be supported by the model ecosystem. Eventually, PoRA wants to be the 'best cluster', in its totally, not just for one cargo type. And maybe the combination of cargo type, the division of cargo types, is different that they now have. This integrated approach of the organisation will reduce the 'columns' within the organisation. Columns of one cargo type, with the objective of making this column as large as possible. This model ecosystem will be a first step towards a more integrated organisation.

If one cannot oversee all the data about particular project anymore, a model ecosystem provides structure and objectivity (not depending on the 'mood of an employee'[13]) A model is more objective and complete than a group of people together.

Added value for clients

With a new project, all type of clients come along, who all want a land slot. A model ecosystem enables PoRA to make a better-trade off. To decide to choose for a particular client, because in his market more benefits are expected. This enables PoRA to have a dialog with customers. By making more reliable statements about plausible futures, PoRA can bring value to the customers[14].

User within PoRA

When a model ecosystem is implemented within PoRA, multiple types of employees will use the system. Both (model) technical trained employees, and non-technical trained employees will have to use, or at least understand, the model ecosystem. This means that the models cannot be black-boxes, only understandable for the developers. Also the users, the board of directors, planners etc. need to understand what a model ecosystem does, what it contributes and how they should use the information gained from this model ecosystem. PoRa, therefore, needs to make sure the emphasize is not only on the technical side, the development of the models, but that the integration within the organisation is just as important.

7.4 Impact of the model ecosystem on the decision-making process

In the previous paragraph, the general impacts on PoRA as an organisation are defined. In this paragraph, it is discussed what the impact of the model ecosystem will be on the decision-making process of PoRA. First the impact on the process is discussed. After that, the impact on the decisions itself is explained.

[13] Translated from: Omdat mensen een deel van de kennis in hun hoofd hebben. Maar hoe objectief is dat, hoe compleet is dat beeld. Is dat de waan van de dag?

[14] Translated from: Joh, wat zijn jouw toekomst ideeën, heb je deze toekomst wel ook in je vizier? Dan kun je bijvoorbeeld praten over consolidatie.

Impact on the process of making decisions
The model ecosystem gives more quantitative support to the decisions. When decisions are made based on a model ecosystem, one know which uncertainties are estimated and what the possible outcomes are. Instead of: this project is not going to work, or: 'it will be fantastic', one will have a better feeling of which factors are taken into account, to make the decision. The impact of the model ecosystem can also be insightfully, more understanding of the different factors can be obtained. 'If this are the considerations, then this means…'. One is forced to review the consequences of particular assumptions, or the probability of these assumptions.

A model ecosystem makes it more explicit what expectations are actually taking into account during the decision-making process, and which ones you don't. And it becomes clear how these expectations are valued. And how much weight do you give to particular factors. These things are made explicit in the model ecosystem.

Impact on the decisions
In the decisions currently made, all the accumulated knowledge of everyone is already implicitly taking into consideration. Because this same knowledge will be used to develop the models, it is expected, that the outcome of the decision is not changing. In principle, the model should therefore lead to the same conclusion as human choices. The model ecosystem, however, can be reinforcing. When the outcomes of the model are the same as the expectations of the employee, the expectations are confirmed. But not only are the expectations confirmed, it can also become clear why something happens. This can strengthen the decision.

But by using a model ecosystem, one gets a sharper why particular decision are made and on what grounds, and which uncertainties are taken into account. A better estimations can be made and you will get rid of the: 'let's just do this'[15]. But eventually, the decisions will get 'better'. Not the go or no go for a particular decision, but especially when the decision has been made. One will know better what to expect, where to be careful and to steer the decision later in the process.

No-regret decisions No model can ever predict the exact future, but a model ecosystem can explore the possible futures. The model ecosystem allows PoRA to see what can be expected. Are there any options that always have a favourable outcome - or always have an outcome that is disadvantageous? It gives PoRA insights in the no-regret options. What should they do in each case. And what should they never do? No-regret decisions are decisions that can be justified from economic, social, and environmental perspectives – whether large changes take place or not. The ability to discover what the no-regret decisions are, reduces and delimits the uncertainty space and they increase the resilience of PoRA. This means that PoRA will be better prepared for possible risks or changes within the environment and can protect themselves against them (or at least try to).

[15] Translated from: Je krijg geen dingen meer van: nou, laten we het maar doen.

This no-regret decision is clarified by the PRIM analysis of the assessment of the new terminal. The results shown in Figure 40-Figure 44 are discussed during the validation session. This example may be not realistic, because the chance that a new coal terminal will be build is almost. But this example does demonstrate how a model ecosystem can support PoRA in making no-regret decisions.

All respondents agree upon the fact that the combinations of assumptions about the uncertainties, leading to the positive assessment of the terminal, are not plausible. This means, that the terminal will only be profitable in a future that is not realistic. Which means that, PoRA should, whatever future may occur, not build this terminal.

7.5 Conclusion

In this chapter the last sub-question is addressed: *How would the implementation of a system of models impact the Port of Rotterdam Authority?*

To answer this question, both the design of the model ecosystem and the results of the proof of concept are discussed in a validation session with PoRA employees. Both the impact on the organisation and the impact on the decision-making process are analysed.

The implementation of a model ecosystem is considered plausible by PoRA employees. When a clear plan is developed, a mental shift can be reached, leading to the implementation of a model ecosystem. However, some people may feel replaced by models. The provision of information and the transfer of knowledge should, therefore, be taken into account carefully, to reduce resistance within the organisation. The model ecosystem approaches the system in a more integrated way, which may lead (on the long-term) to more profound changes within the organisation

The model ecosystem will impact PoRA in a positive manner because of the following:

- The ability to integrate the different components from the 'Haven Ontwikkelings Cyclus' and explore the whole chain rather than individual elements.
- The ability to explore a wide range of plausible futures, rather than the five scenarios.
- The coupling of the models gives a more consistent image of the system.
- PoRA can bring value to the customers.
- A model is more objective and complete than a group of people together.
- Support PoRA to become a more integrated organisation .
- By the implementation of automated simulation tools, time is saved with the analysis.
- More insights into the complexities that should be taken into account in the decision-making process.
- Decisions will be better substantiated, deliberately, and informed by a model ecosystem. This makes it more easy to justify particular decisions.
- PoRA will be aware of the possible changes that can happen in the future, which lead to less surprises.
- The model ecosystem enables PoRA to discover what the no-regret decision are.
- The model ecosystem dams the future and reduces the uncertainty space.

8

Discussion

In this chapter, the outcomes of the research are placed in a broader context. This is done by, first, elaborating on the interpretation of the results of the model ecosystem. The results are interpreted based on the assumptions that are made, the proof of concept that is developed and the sampling methods that are used. Given these assumptions, what can one say about the results? After that, the generalisability of the developed design is explained. Based on the experiences with PoRA, this chapter explores how this could be translated to other, similar, organisations. In the third paragraph, the limitations of the research are discussed. Based on this, both the recommendations for scientific research, as the recommendations for PoRA about next steps, are given.

8.1 Interpretation of the results

The result of this research is a design of a model ecosystem and a proof of concept of this design, applied to the coal case of PoRA. This proof of concept consists of multiple simple and small models. The objective of the individual models is to obtain output that represents the dynamics of the system. In this research it is, therefore, less relevant to focus on the interpretation of the exact figures of the outcomes of the model ecosystem. What is more important, is to focus on how to interpret the meaning of this kind of output. Regardless of the form and content of the model ecosystem, what can PoRA say about the future based on these types of outcomes, what does it mean for PoRA that the uncertainty space is that large?

The system of PoRA is becoming more and more complex and many uncertainties exist. The knowledge and capabilities of employees to make reliable statements about the future may not be enough anymore to make decisions based on gut-feelings. Besides that, the fact that the space within the port area is becoming scarce and it cannot just be assumed that throughput of all cargo types keeps increasing, makes the impact of the decisions increase. The decision-making process of PoRA has not grown along and has not been adapted enough to control this growing complexity and uncertainty. PoRA is not able enough to treat this complexity in a systematic way. In this research it has become clear that a model ecosystem could support PoRA to make them more capable of withstanding these complexities and uncertainties. However, a model ecosystem will not necessarily change the content of the decisions made by PoRA. What it does change, is the process of making the decisions.

By applying EMA to the model ecosystem the full range of plausible futures can be explored. This allows PoRA to gain more insights in 'what may happen'. It enables PoRA to explore possible futures, despite that fact that uncertainties are sampled from a uniform distribution and that correlations between uncertainties are not taken into account. However, for PoRA it is important to realise that, even when a very detailed model ecosystem will be implemented, they will never be able to predoict the exact future. But the model ecosystem does allow them to gain more insights in these futures. When models are made that represent the dynamics of the system, decisions will be more quantitative substantiated and decisions will be taken more deliberately. It allows PoRA to take no-regret decisions. And once decisions are taken, they are much better prepared for changes that may affect the projects or the developed strategy.

The use of EMA applied to a model ecosystem changes the way in which the uncertain future is approached. Rather than developing tools that can calculate a small piece of the system, the system of PoRA is approach as an integrated system. The different elements within the decision-making process are not individual elements anymore, with their own objective of 'calculating' and estimating particular outcomes. The model ecosystem enables PoRA to explore what impact changes in the environment have on the system, throughout the entire decision-making chain. Through this way of using models, the focus shifts from focusing on the right data of one particular element and developing as detailed models as possible, to focusing on what types of futures may occur and in what way PoRA can develop a robust strategy, resistant to this unpredictable and uncertain future.

8.2 Model coupling

In Chapter 1, several challenges are mentioned that could be encountered when developing multi-model systems. Within the coupling phase in this research, an attempt is made to overcome these challenges in different manners.

Multi-scale Within the model ecosystem, multiple components differ in scale, both on geographical scale and time scale. The largest scale difference within this model ecosystem is present between the long-term global forecast component and the satisficing component. These components differ at both at geographical scale and time scale. The geographical scale difference is aimed to be solved by adding an extra component to the model ecosystem: the throughput Rotterdam component. This component translates the global scale coal demand model to the local satisficing model by adding the market share of Rotterdam. The time scale difference is aimed to be solved by letting both the components have time steps of 1 year. Even though the distribution of throughput over different terminals may change from day to day, it is of more importance to evaluate what happens within a year, whether big changes may happen within that time period. The coal demand model will give the throughput per year, in this way the two components are able to communicate with each other (via the master). The proof of concept demonstrates that adding an extra component to solve the scale difference is a suitable solution.

Uncertainties In the introduction, two types of uncertainty are named, the deep uncertainty caused by the uncertain environment of the port area and the model uncertainty. EMA is applied to the model ecosystem in order to tread the deep uncertainties systematically. By applying EMA, a wide range of the uncertainties can be discovered and analysed. By performing an uncertainty analysis on the entire model ecosystem, the uncertainties throughout the entire decision-making chain can be assessed. The model structure uncertainty would ideally be solved by developing multiple models and evaluate the outcomes from the different models, however, due to time limitations this deepening step is not performed.

Formalism As mentioned before, different modelling and coupling techniques are used in the development phase. The fact that not all these languages can communicate directly, complicates the coupling of various components. The master-slave construction applied in this proof of concept demonstrates that this concept is suitable and eases the coupling process.

Use of existing models The model ecosystem is designed with a high degree of modularity, in such a way that the different components should be easily replaced. The replacement of the R components is a good example. The ability of replacing models (of different formalisms) shows that the modular character of a design enables the replacement of components by other, existing, components. In this proof of concept, the added value of a master-slave construction is demonstrated. This masters-slave construction enables the existence of the heterogeneous system of components, and ensures that the components can be integrated seamlessly. It has demonstrated that the concept is working, that existing and new models can be used interchangeable within a model ecosystem.

8.3 Generalisability

At the start of this research it was chosen to focus on the case of PoRA and develop a design and a proof of concept that is applicable to their decision-making process. This research choice has both advantages and disadvantages. Because the scope is limited to one specific case, it allows one to dive deeper into the specific characteristics of the decision-making process of this particular case. The large advantage it has for PoRA is that the narrowing of the scope of the research to their specific case, is the contribution is has for PoRA. Because the design is tailored for their case, the usability for PoRA is high. For the research itself it is easier to gain information and dive deeper into this specific case. The disadvantage is that it is not possible to apply the design to another case. A possible solution to translate this specific design to a more general design, would be to apply the design to another similar case. One can explore which elements are applicable to other cases, and which elements of the design are only usable for this specific case. When this is done for multiple other cases, a design could be developed that consists of general elements, that count for all similar cases, and elements that are case specific. Because the design is developed at multiple levels, the first level (high-level design) could function as the base for the general design, applicable to other systems such as the port area. The second level (the detailed design) could be used to translate the general design to the specific case. Examples for whom such a model ecosystem could be interested are ProRail or Schiphol. Even though the system and the decisions they make are not the exact same as those of PoRA, the characteristics are the same. These organisations are also part of a socio-technical system in which a high degree of uncertainty exists, and the decisions they make are also characterised by their high investment costs and long durations. An example of what such a translation would look like is shown in Figure 45.

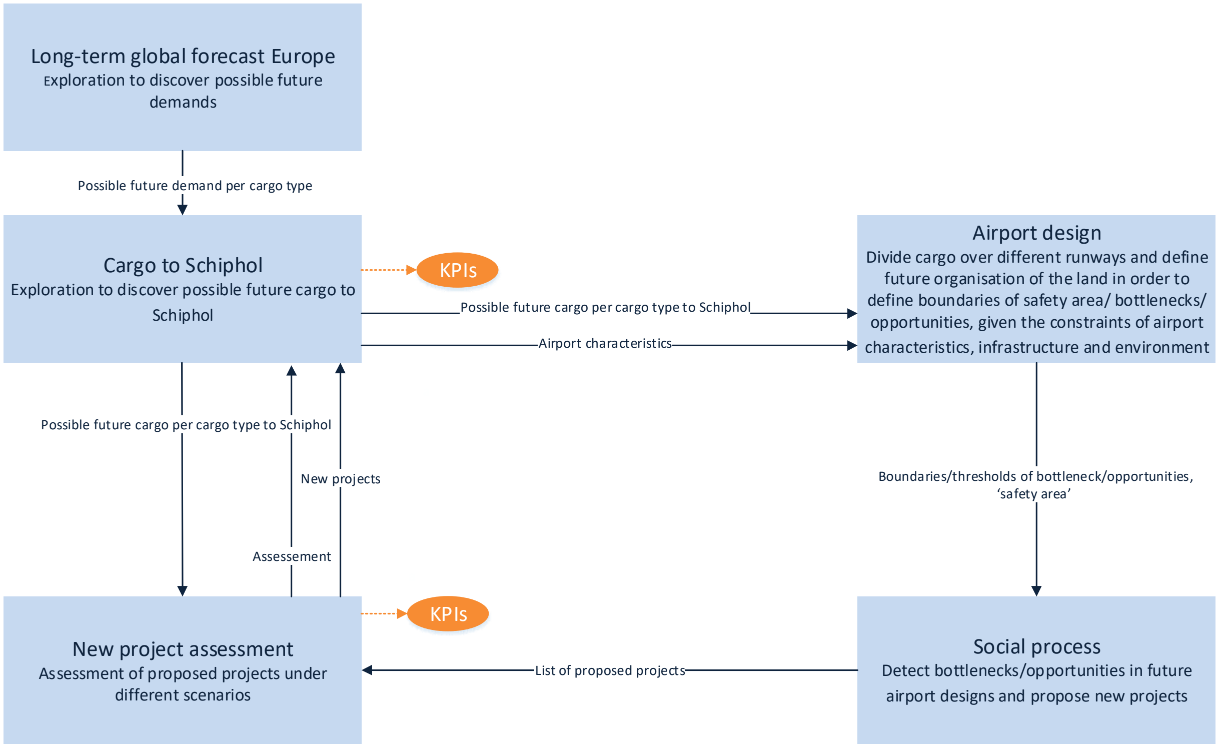

Figure 45: Application of level 2 on Schiphol case

8.4 Limitations of the research

In this research, a model ecosystem for the decision-making process of PoRA is designed, in which the use of models is improved. PoRA is not the only large organisation that struggles with dealing with an uncertain and unpredictable future, the translation of long-term scenarios to strategic and operational decisions and the use of models in their decision-making process. Because the research is done on behalf of, and in collaboration with PoRA, the scope of the research is narrowed to their system. This limits the ability to apply this design directly to other, similar, cases.

A second limitation is the lack of the ability to validate the model outcomes. The validation in this research is done by comparing the model outcomes to the outcomes of the current models or based on expert knowledge, but a true validation is not possible. Precisely because the future is uncertain and unpredictable, one does not know what the outcomes of a model should be exactly. It is only possible to assess the model outcomes and judge whether they are considered plausible or not.

8.4.1 Limitations of the implementation of the proof of concept

- What is missing right now is that there is only coal in the model. When throughput is high, income will be high, when throughput is low, income is low. However, you do not see the 'opportunity costs'. An empty terminal does not 'cost' the port money directly, but it obstruct income from an alternative terminal or other type of business.

- Infra capacity is per terminal, total capacity of area is not included.
    - If new terminal is realised, it can be checked whether infra bottlenecks occur.
- Terminal never has 100% occupancy, because there is the infrastructural limit that doesn't match the full capacity.

8.5 Recommendations for further research

- The current proof of concept is built with a master slave construction. For further research it would be interesting to develop a model ecosystem with individual models that are coupled directly and communicate directly, without the interference of a master-component. Instead of a sign from the master-component, the models are triggered by messages from the other models. This way, a model ecosystem with autonomous, communicating models is developed.
- It the current design, a 'social process' component exists. For future research it would be interesting to develop an algorithm that assesses the model outcomes in such a way that the social component will not be necessary anymore.
- In the current proof of concept, one model for each of the components is developed. For further research it would be interesting to develop multiple plausible models for each of the components. These different models should, then, be approached as an additional uncertainty that could be varied.
- As mentioned in the previous paragraph, the design of the model ecosystem could be translated to a generic design. Further research to this translation will allow other organisations to use the design. This research should explore which elements of the design are general and which elements are case specific. A design should be developed that is applicable to other cases, and in which other organisations can easily include their own case specific elements.

8.6 Recommendations for the Port of Rotterdam Authority

In this research, a model ecosystem is designed and a proof of concept of this design is developed. For this proof of concept, small and simple simulations models are used and only one cargo type is included. For PoRA it would be interesting to develop a model ecosystem which includes the existing models, based on the current, realistic, data of the port area, and contains the entire range of cargo types (including not yet existing or upcoming cargo types). For the implementation of a model ecosystem some aspects ask for further research:

- In which formalisms are the current models developed and what are the coupling possibilities of these models?
- For port authorities in general it is hard to estimate the precise capacity of the terminals within their port area, even for the terminals it is hard to provide exact data about their capacity. Further investigation of this data is needed in order to make more realistic models.
- For this proof of concept, the ranges for the uncertainty space are determined based on literature. For PoRA, it is of importance to negotiate which ranges they consider plausible.
- In the current proof of concept, only one cargo type is modelled. To explore the interaction between the various cargo types, PorA should include multiple long-term global forecast models in the model ecosystem.

During the expert consultation in the final phase of this research, the question was posed: what is needed to implement a model ecosystem within PoRA? The first answer of all the respondents was: mind-set! This implies that PoRA may not be ready yet to implement such a model ecosystem. It is therefore of great importance for PoRA to develop a clear plan in which they can communicate the essence and the importance of a model system and explain what the added value is for PoRA. This plan should attempt to transform the attitude against such a system.

8.7 Contributions of the research

This research has both a scientific contribution and a societal contribution. The societal contribution is two folded: a societal contribution in general and for PoRA specific.

Scientific contribution In this research, multiple formalisms and modelling techniques are used and coupled. This research addresses the possibilities of coupling these various techniques, what should be taken into account when coupling them and what the consequences are of these couplings. This information could be used when future model ecosystems are developed.

General societal contribution The design that is developed in this research can support organisation like PoRA in their decision-making process by approaching the uncertainties within a model more systematically. When PoRA and other similar organisations can make more grounded forecasts and strategic decisions, the global economic position of these stakeholders will be strengthened.

Port of Rotterdam Authority Within PoRA, a mental shift is needed in order to create a more data-driven, model based decision-making process. This research is a first step to present the possibilities of a model ecosystem, what new capabilities become available when a model ecosystem is implemented and demonstrates what the added value for PoRA is of such a system. It presents in what way PoRA can approach the uncertainties within their system and how they can get more grip on them.

9

Conclusion

Chapter 1 explained that PoRA struggles with making reliable statements about possible futures and that this hinders the ability to make robust strategic and operational decisions resistant to this increasingly uncertain and unpredictable future. The issues that PoRA is facing are affirmed in literature. One possible approach to treat uncertainties in a more systematic way, is to develop a system of models. The identification of these issues has led to the following main research question:

How can a system of models support the Port of Rotterdam Authority in their decision-making process?

Chapter 2 explained that a suitable method is to approach the system of models as a model ecosystem. This research is aimed at exploring the added value of a model ecosystem for PoRA. In order to do so, three sub-questions are answered. The answer to these sub-questions are addressed in the following paragraphs.

How is the current decision-making process of the Port of Rotterdam Authority organised and what are the challenges encountered in this process?

Based on interviews with experts, a system analysis has been performed. An overview of the current decision-making process of PoRA is shown in Figure 46.

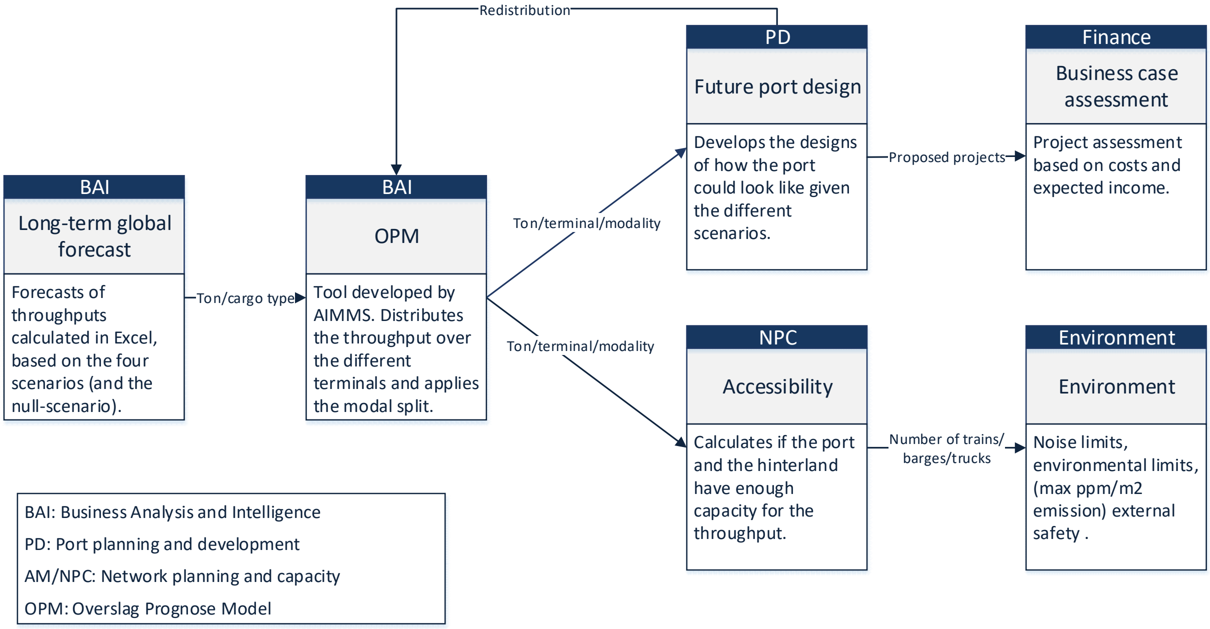

Figure 46: Overview of decision-making process PoRA

The main process elements in the decision-making process of PoRA are:

- development of long-term global forecasts
- development of port designs
- perform environmental checks
- assess infrastructural capacity
- develop the corporate strategy
- assess proposed projects.

The most important challenges encountered within this decision-process are the lack of connection between models of the different departments, the use of Excel which is error-prone, labour-intensive and time-consuming, and the fact that only five (or sometimes only one) scenarios are used in the assessment of new projects and port designs.

In what way can a system of models help in overcoming the challenges faced by the Port of Rotterdam Authority in their decision-making process?

Figure 47 shows the design of a model ecosystem that helps in overcoming the challenges encountered by PoRA. This design consist of five components, which all relate to one (or multiple) functional requirement. In this design, most of the challenges are addressed. The most important characteristics of this design are the modularity, use of automated tools, the coupling between the various components and the strict definition of input and outputs of the components. Due to the modularity, it is possible to replace or adjust the components, without changing the entire model ecosystem. In this way, new and existing models can be used interchangeably. Because the components within the model ecosystem are coupled, PoRA is able to explore the entire chain within the decision-making process. Due to this coupling and due to the use of automated tools, PoRA can explore and assess what impact particular changes in one of the components have on the rest of the system.

By applying EMA to the model ecosystem, new capabilities become available to explore the uncertainties that PoRA is facing. The model ecosystem enables PoRA to explore the entire set of plausible futures. By using scenario development, PoRA is also able to develop narratives that describe the various uncertainty subspaces in which different types of future paths are grouped. It gives insights in the uncertainty subspaces that lead to particular (desirable or undesirable) outcomes. These subspaces can be translated to *communicable, internally consistent, and plausible narratives.* The four main types of future paths are:

1. monotonically increasing
2. monotonically decreasing
3. non-monotone, starting with a decrease
4. non-monotone, starting with an increase.

When the path is monotone, the path either increases or decreases over time. When the path is non-monotone, the path changes direction during the coming 40 years.

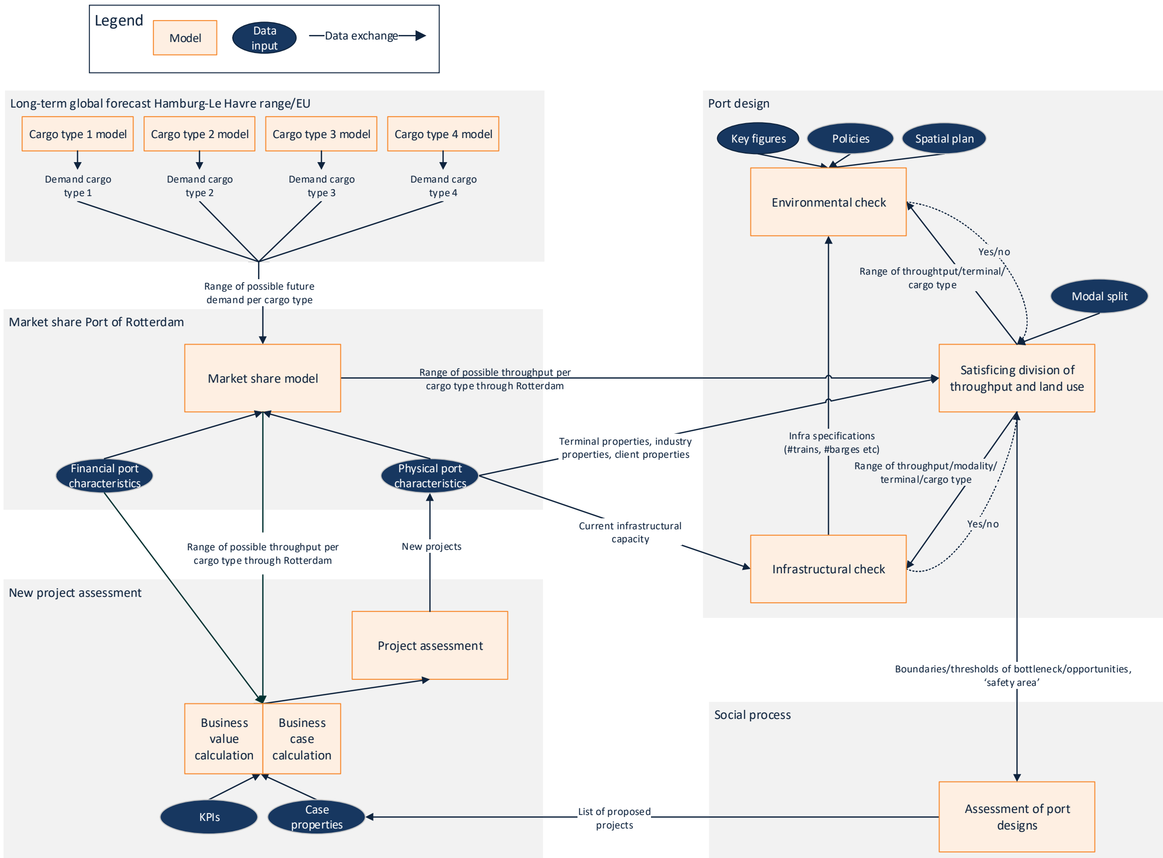

Figure 47: Design of level 2

How would the implementation of a system of models impact the Port of Rotterdam Authority?

The model ecosystem will impact PoRA in a positive manner because of the following:

- The ability to integrate the different components from the 'Haven Ontwikkelings Cyclus' and explore the whole chain rather than individual elements.
- The ability to explore a wide range of plausible futures, rather than the five scenarios.
- The coupling of the models gives a more consistent image of the system.
- PoRA can bring value to the customers.
- A model is more objective and complete than a group of people together.
- Support PoRA to become a more integrated organisation .
- By the implementation of automated simulation tools, time is saved with the analysis.
- More insights into the complexities that should be taken into account in the decision-making process.
- Decisions will be better substantiated, deliberated, and informed by a model ecosystem. This makes it easier to justify particular decisions.
- PoRA will be aware of the possible changes that can happen in the future, which lead to less surprises.
- The model ecosystem enables PoRA to discover what the no-regret decision are.
- The model ecosystem dams the future and reduces the uncertainty space.

Based on the answers to the sub-questions, the main research question can be answered:

How can a model ecosystem support the Port of Rotterdam Authority in their decision-making process?

With a model ecosystem, PoRA is armed with a set of tools to address the challenges encountered in their decision-making process, both the practical challenges and the challenges regarding the deep uncertainty. It eases the decision-making process, because the system is approached in a more integrated manner and most of the practical issues are solved (e.g. use of Excel, inconsistency, inefficient loops etc.). In addition, with the model ecosystem in combination with EMA, new capabilities become available to explore uncertainties. It enables PoRA to approach the uncertainties in a systematic way. The decision, itself, may not always change, but the process of making this decisions will be different. Decisions will be better substantiated, deliberated, and informed by a model ecosystem. This makes it easier to justify particular decisions. The model ecosystem dams the future and can reduce the uncertainty space. By reducing this uncertainty space, a model ecosystem enables PoRA to make no-regret decisions, which makes them more resilient.

10

Reflection

This research is performed on behalf of PoRA. The fact that I could explore the current system of PoRA and that I was able to interview people from all different departments, made this research more interesting. And because the design is applied to a real case, and a real system, the outcomes of the model ecosystem could be discussed with experts. These validation sessions resulted in very interested outcomes. However, this choice also narrowed the research scope. It may have been more interesting if the first design would have been a generic model ecosystem, applicable to all organisations that deal decision-making under deep uncertainty, and of whom the decisions are characterized by their long duration and high costs. After the design of a generic model ecosystem, this design could have been applied to the case of PoRA.

Model ecosystem

Within this research, the system of models is approached as a model ecosystem: '*sociable individuals coevolving with one another in a changing environment* ' (Bollinger et al., 2015). Here, existing and new models can be used and integrated, coupled where needed and interact with one another. This almost sounds like freedom and euphoria, but in this research the contrary is proved. In the model ecosystem, the different components need to be integrated seamlessly with each other. In this proof of concept it becomes clear that, even when only small and simple models are used, the coupling of these models asks for a lot of effort: interfaces must be very clear and that without strict rules the couplings are not possible. The different components within the ecosystem are coupled in a particular way, which creates a certain balance. This means that, once a model ecosystem is developed, there are consequences down the line, in future models. It will be difficult to 'just' add an extra component. The component needs to be integrated within the model ecosystem, and a new balance should be found.

This ecosystem approach, however, could even be pulled further. The organisation itself could be approached as an ecosystem too. And the development of a model ecosystem is a first step in this process.

Complexity of the models

Many studies have been done on the development of really detailed and complex simulation models. How far should PoRA go in the development of such detailed models? One can go far, developing models could take years, and could lead to runtimes of months. The proof of concept has shown that one can gain much information from the model ecosystem, even when the exact data about the system is not completely known and the models do not contain all the details of the system. This research shows that, even if a model ecosystem is not based on real data, and consists of simplified models, PoRA can still explore what possible futures exist. Because a wide range of plausible futures is explored, the way in which these plausible futures have come about is less relevant. If the model ecosystem will be implemented with more extended, detailed models, consisting of lots of different factors, and more dynamic relations, the variety of outcomes will still be large. Everything that is added to this complexity, also means that more data is needed, get more variables that are uncertain, which leads to an explosion of the variables. Making more detailed models does not take the uncertainty and unpredictability of the system away. The key point is, that a model should represent the dynamics of the systems, and whether these dynamics have been established by a model of 50 factors, or a model of 5000 factors, is less relevant.

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Appendices

Appendix A: Interviews

A.1 Interview questions

1. Hoe zou u het proces van de vertaling van lange termijn modellen naar strategische en operationele planningsbeslissing beschrijven?
2. Is uw afdeling betrokken bij dit proces, zo ja, op welke momenten?
3. Wat is de rol van uw afdeling binnen dit proces?
4. Hoe verloopt de interactie tussen uw afdeling en de andere betrokken afdelingen in dit proces?
5. Hoe zijn deze modellen op dit moment ingepast in het proces van de afdeling?
    a. Bij welke besluitvorming worden deze modellen gebruikt?
    b. Hoe vaak worden deze beslissingen genomen?
    c. Wat is de doorloop tijd van deze beslissingen?
    d. Welke andere informatie wordt er nog gebruikt?
6. Wat zijn de challenges?
    a. Wat zijn knelpunten binnen het besluitvormingsproces?
    b. Wat voor impact hebben deze knelpunten?
    c. Wat zou je liever anders zien in dit proces, wat zou bedragen aan het overwinnen van deze challenges?
7. Welke onzekerheden spelen de grootste rol?
    a. Welke factoren zijn het meest onzeker?
    b. Welke factoren hebben de grootste impact?

A.2 List of respondents

- Rinske van der Meer – environment – 30-5-2017
- Nicolette Ammerlaan – AM/NPC – 30-5-2017
- Xu Jao Pan – 24-5-2017
- Michiel Nijdam – Corporate Strategy – 23-5-2017
- Ester Falkena – AM/NPC – 2604
- Caroline Kroes – Corporate Strategy 12-5-2017
- Noortje van der Burgt – BAI – 2-5-2017
- Kevin Kruijthoff – BAI – 2-5-2017
- Twan Romeijn – BAI – 2-5-2017
- Ronald Kalkhoven – BAI – 2-5-2017
- Hugo du Mez – BAI – 1-5-2017
- Ronald Backers – BAI – 1-5-2017
- Jelle Peddemors – PD – 24-4-2017
- Anneke Vaes – BAI
- Caramay Schmelzer – Corporate Strategy – 10-5-2017

Appendix B: Scenarios

The scenarios are based on two main drivers which are a summary of the most determining underlying drivers:

- energy and climate
  - approach to climate change
  - type of energy generation
  - type of energy innovation
  - desirable energy mix
  - geopolitics
- economy and world trade
  - economic growth
  - world trade
  - geopolitics.

Within the scenarios also three trends of which the direction is already defined: climate change, energy efficiency and energy demand

B.1 Qualitative scenarios

As mentioned before PoRA developed five long-term global scenarios. In the following paragraph a brief summary of the scenarios is given.

Conservative Carbon (CC) In CC there is a low economic growth. Large influential multinationals focus on their short-term economic interests and policies of (large) countries are rather protectionist. They have a reduced impact on globalisation and international trade. Limited climate policies exist and energy is mainly produced centrally. The focus is on incremental innovation and fossil energy (mainly oil) remains the dominant energy. Sustainability is still a large expensive and a delayed focus on energy efficiency exists. The energy prices continue increasing and pressure exists on the energy-intensive industry.

Fossil Forward (FF) In FF the economy is growing above average, international trust and a strongly growing international trade are leading to a properly working hub & spoke system. The focus lies on 'clean fossil energy', the cheap coal continues to hold an important share in the energy mix due to a good working CCS-system.

Lean & Green (LG) In LG there is hardly growing economy. The sustainability is picked up at a national level. The high expenses remain which leads to competition between countries, this impedes free trade. Both society and the economy are becoming greener, but subsidy and taxation policies provide inefficient solutions. This also applies to logistics.

Green Unlimited (GU) In GU the economy is growing above average. Governments stimulate international trust and an international approach regarding climate issues. Sustainability is seen as an opportunity and due to radical innovations it is competitive with fossil energy. An accelerated energy transition takes place with decentral and sustainable energy systems and focus on energy saving. This together leads to cost savings and new markets for industrial clusters. Shale gas loses part of its share in the energy mix.

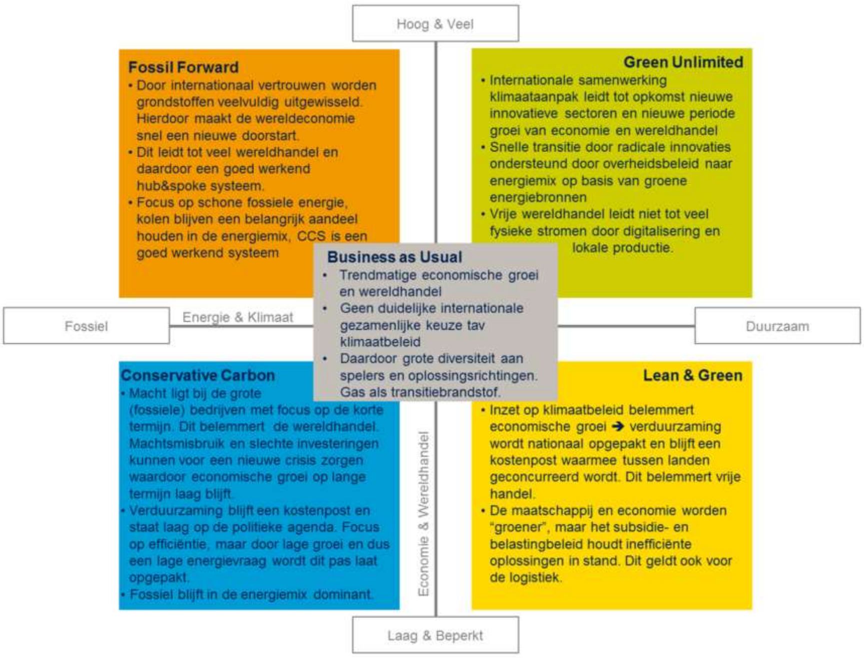


Figure 48: Visual of the four scenarios

Appendix C: Objective tree – Corporate Strategy

Appendix PoRA VI (Corporate Strategy)

Appendix D: Uncertainties

Category	Uncertainty	Impact on system	Relevant cargo category	Relevant cargo type

Energy	Energy transition	• Throughput raw materials
		  ○ Reduction oil demand
		  ○ Reduction coal demand
		• Reduced production (?)
		• Increased demand green energy
		  ○ More space for wind/solar energy
		  ○ More biomass
		• Energy efficiency
			Liquid and dry bulk	All

	Energy mix		Liquid and dry bulk	All
	Ratio fossil/sustainable		Liquid and dry bulk	All
	Climate change		Liquid and dry bulk	All
	CO_2 price		Liquid and dry bulk	All
	CO_2 reduction		Liquid and dry bulk	All
	Sustainability (phase out of fossil)		Liquid and dry bulk	All
	Future substitution of fossil		Liquid and dry bulk	All
	Speed of energy transition		Liquid and dry bulk	All
	Volatile prices raw materials (low prices)	• Decreased TP bio-based • Increased TP fossil		
Geopolitics	Governmental policies	•	All	All

	EU	• Trade climate
		  ○ Trade limitations
		  ○ Import charges
		  ○ Trust
			All	All

	Brexit	• Less trade with UK	All (RoRo most)	
	Paris Agreement (can be an event that influences energy transition factor)	• Speed up energy transition	Liquid and dry bulk	All
	Protectionism	• Import charges • Trade limitations	All	All

	Conflicts Middle-east → More immigration → Closed borders	• Trade climate
		  ○ Trade limitations
		  ○ Import charges		

		• Trust • Higher costs of world trade		
	One-belt-one-road	• Influence trade with China		
	Trump	• World trade		
	Decreasing growth Chinese economy	• World trade		
	Changing society	• Shift of job types		
Demographic	Population composition	• Economic growth	All	All
		•		
	Aging	• Economic growth	All	All
	Changing consumption patterns	• Throughput different cargo types	All	All
Logistics	Changing prices		Breakbulk	All
	Location of production (decentral)	Less world trade	Breakbulk	All
	Digitalisation	• Chain efficiency • Decreased logistic chain cost		
Other	Economies of scale		All	All
	Future of PoRA		All	All
	Market development		All	All
	New markets		All	All
	Additive manufacturing (3D printing, laserprinting → changing production location)	• Different type of cargo types transported • Less world trade (containers) • Increased chemical production	Breakbulk Liquid bulk	All
	Upcoming South-European ports	• Less throughput of all cargo types	All	All
	Dependence		All	All
	Alliance formation	• Changing TP of containers to Rdam (expected to increase)	Breakbulk	All
	Consolidation of container ships	• Changing TP of containers to Rdam (expected to increase)	Breakbulk	All

	External trading shocks		All	All
	Exchange rates		All	All

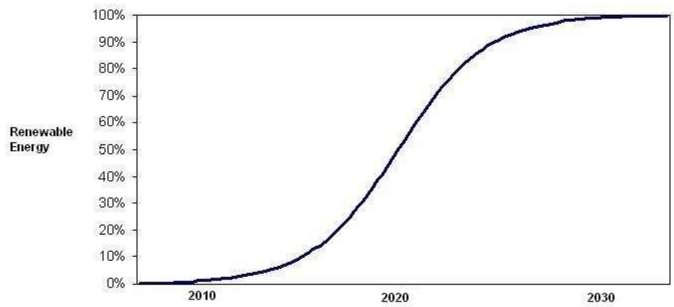
Appendix E: Software implementation

E.1 Coal demand

The coal demand model consists of a set of equations implemented in Python. The coal demand is determined by three variables: the share of green energy (% of total energy demand), the share of other grey energy sources (% total grey energy demand) and the total energy demand. It is chosen to implement one uncertainty for every factor in de coal model.

Share green energy The most important uncertainty influencing the share in green energy is the path of the energy transition. In this model the energy transition is modelled as a traditional transition S-curve shown in Figure 49 (Schilling & Esmundo, 2009).

$$Share\ green\ energy\ =\ c * ((a * (t - u)) + 1)$$



es

Figure 49: S-curve of energy transition

This function has 4 variables: c, a, t and u. Where t stands for the time in years.

c determines the end value of the transition. It demonstrates what the share of green energy is at the end of the curve when the transition is completed. The higher the value of c is, the higher the final share of green energy.

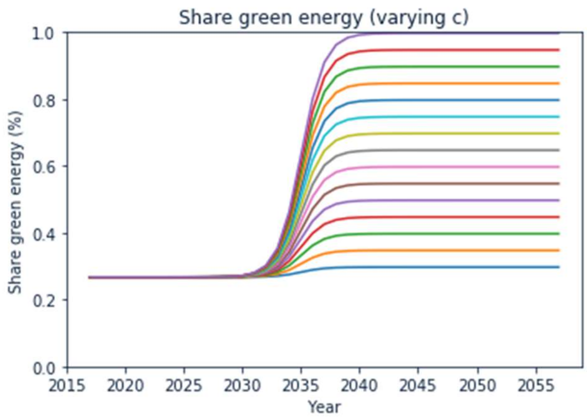


Figure 50: Share green energy (varying c)

a determines the speed of the transition at the acceleration point. If a is high, the energy transition takes place fast within a short period of time.

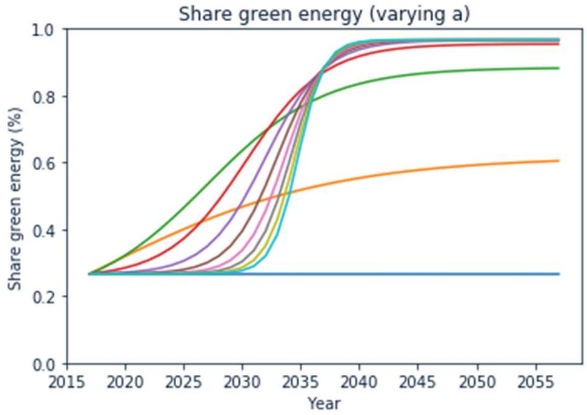


Figure 51: Share green energy (varying a)

u determines the moment on which the energy transition takes place. The higher the value of u, the later the transition takes place.

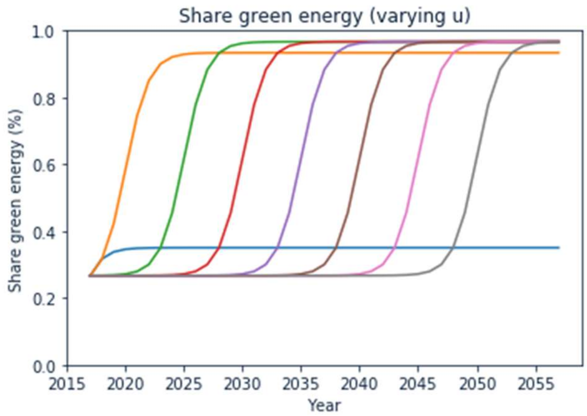


Figure 52: Share green energy (varying u)

By combining the different values of the variables distinctive transition path are created, as can be seen in Figure 53. These different path can eventually be translated to a 'story'.

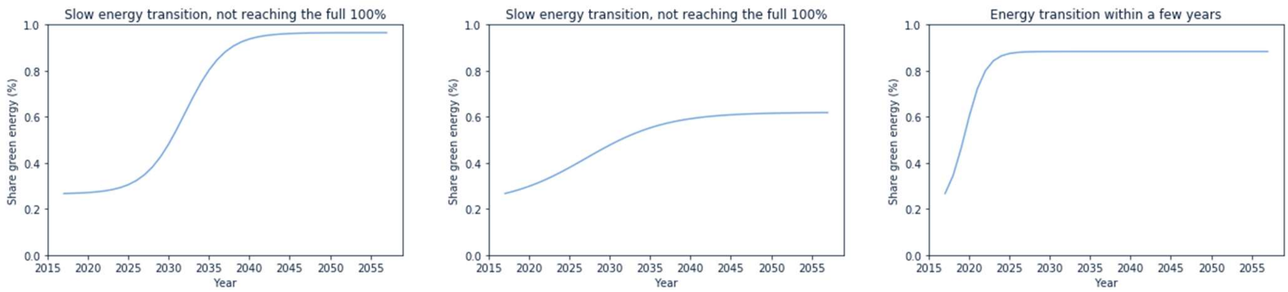


Figure 53: Types of transition paths

Energy demand In this model the energy demand is modelled as a value growing over time, influenced by a growth factor. This growth factors is partly determined by the GDP (Omri, 2013) (Boretos, 2009).

$$Energy\ demand = inititial\ energy\ demand + (inititial\ energy\ demand *\ growth\ factor) * t$$

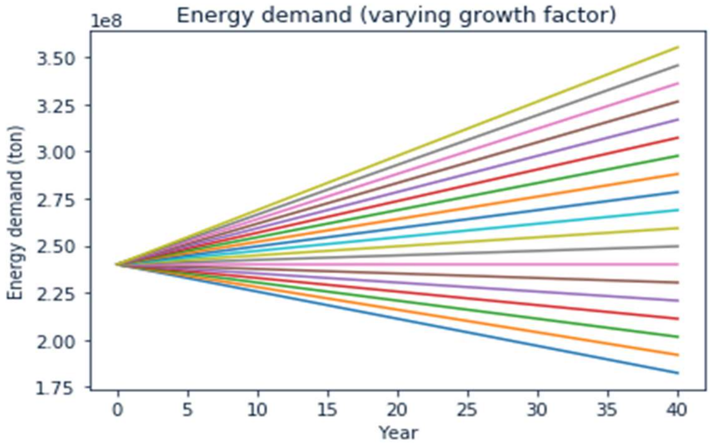


Figure 54: Energy demand

Share of other grey energy sources in energy mix This share is implemented in the same way as the energy demand, an initial value growing over time, influenced by a growth factor. This growth factor can later be translated to a specific variable, for example the facing out of gas, the rrise of nuclear energy in the energy mix or other energy sources:

$$Share\ other\ grey\ energy\ sources =$$
$$initial\ share\ of\ other\ grey\ energy\ sources + \ (initial\ share * growth\ factor) * t$$

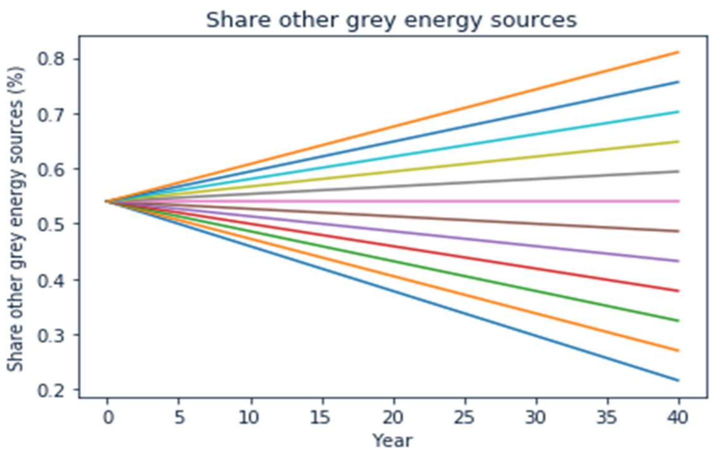


Figure 55: Share of other grey energy sources in energy mix

E.2 Market share Rotterdam

Name	project_1	project_2	project_3
starting_year	2030	2020	2040
MS_AV	0.01	0.02	0.03

Figure 56: Overview of new projects

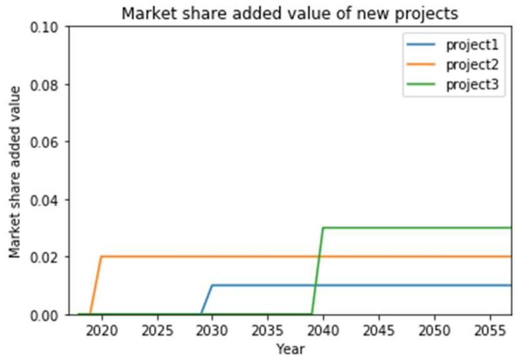


Figure 57: Added value of new projects

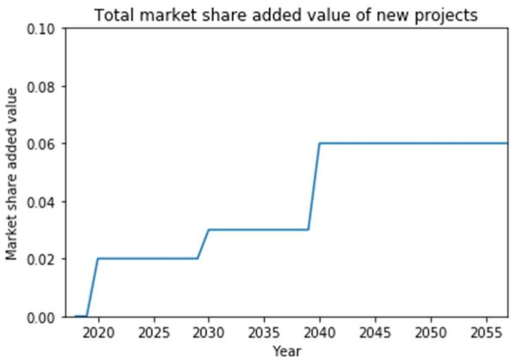


Figure 58: Market share added value of Rotterdam

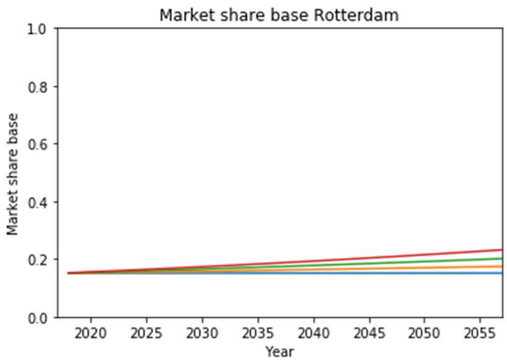


Figure 59: Base market share (varying growth factor)

E.3 Satisficing model

The input for the model is shown in Table 10, Table 11 and Table 12 . Even though the infrastructure and environment model are integrated within the satisficing Netlogo model, the input and output variables will be treated as if they were from separated models.

Table 10: Input and output data of the satisficing Netlogo model

Variable type	Variable	Source
Input	Throughput coal to Rotterdam per year	Market share model
	Terminal characteristics - name - area - surface - capacity - expansion possibility - cargo type - modal split	Port properties

	- infrastructure capacity	
	Area characteristics - name - CO_2 emission limit	Port properties
Output	Terminal output - terminal capacity - terminal capacity unused - terminal TP - terminal occupancy - terminal capacity expanded - terminal capacity initial - terminal denied infra cap - terminal surface	
	Area output - area capacity - area capacity unused - area TP - area occupancy - area denied infra cap - area denied cap percentage	
	General output - TP without terminal - total TP Rotterdam - total surface terminals	

Table 11: Input and output data of the infrastructure Netlogo model (subsystem)

Variable type	**Variable**	**Source**
Input	Terminal input - ton throughput per truck - ton throughput per train - ton throughput per barge	Satisficing model
	Key figures - ton per truck - ton per train - ton per barge	Port properties
	Area characteristics (infrastructure capacity) - maximum number of trucks per area - maximum number of trains per area - maximum number of barges per area	Port properties
Output	Terminal output - number of trucks - number of trains - number of barges	

	Infrastructure check output - ton per terminal fits yes/no	

Table 12: Input and output data of the environment Netlogo model (subsystem)

Variable type	Variable	Source
Input	Terminal input - number of trucks - number of trains - number of barges	Satisficing model
	Key figures - CO_2 emission per truck - CO_2 emission per train - CO_2 emission per barge	External factors
	Area characteristics (infrastructure capacity) - Maximum CO_2 emission per area	Port properties
Output	Infrastructure check output - ton per terminal fits yes/no	

E.4 Business case and Port of Rotterdam business value calculation

As mentioned earlier, the scope of the implementation consists of three types of projects: issue of land for terminals, infrastructure projects and commercial actions. The calculation for the expected income flow differs for the three types of projects. For the issue of land for terminals the expected throughput and the additional surface of that specific terminal will be used in the calculations. The equation for the calculation of the income of a land issue project and the source of the data are shown in Figure 60.

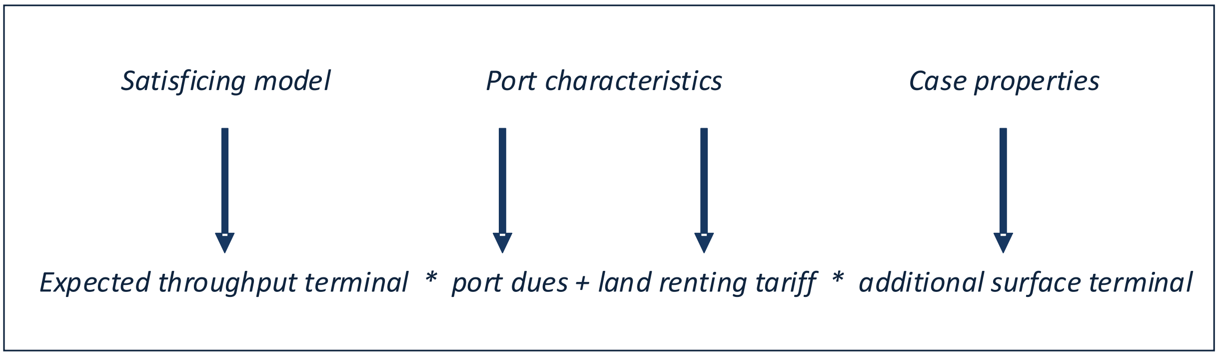


Figure 60: Calculation of expected income - issue of land for terminals

For an infrastructure project and a commercial action, the calculation of expected income is the same, the expected additional throughput for the entire port area will be used for the calculation of the income flow. This expected additional throughput will be calculated by extracting the expected throughput with and without the infrastructure project. The equation for the calculation of these projects and the source of the data is shown in Figure 61.

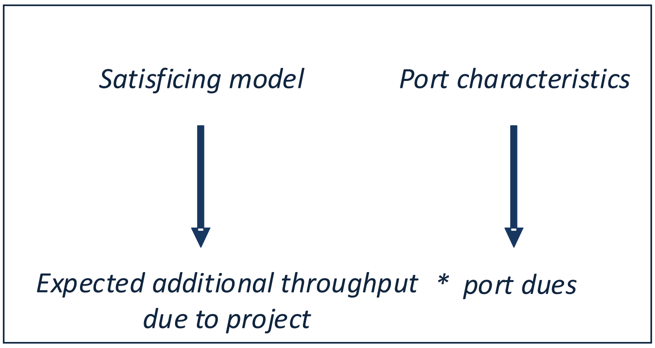


Figure 61: Calculation of expected income – infrastructure project and commercial actions

After the calculation of the expected income, the NPV of the project will be calculated. The NPV will be calculated as followed:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

Where:

$C_t = net\ cash\ flow\ of\ particular\ period\ (expected\ income - operational\ costs)$

$C_0 = initial\ investment\ costs$

$r = discount\ rate$

$T = duration\ of\ project$

The business value of PoRA will be calculated by calculating the expected total income of a given time period.

Appendix F: Coupling challenges

Zero-based indexing Most programming languages are zero-based indexed, that means that they start counting at 0. However, Excel is a one-based indexed language, which means that Excel does not start counting at 0, but at 1. When coupling Excel and Netlogo, one needs to be aware of this difference.

Commas and dots Python and Netlogo both have a different way of presenting lists. In Python the elements from a list are separated by commas. In Netlogo the elements of a list are separated by spaces. Therefore the lists from python needs to be converted before they can be send to Netlogo. This is done by making a string of the Python list and add [] in the communication command. The same happened with the coupling of Excel and Python. In Excel decimals are indicated with a comma, while in Python commas are indicated with dots.

Location of libraries When Netlogo used particular libraries, these libraries are saved at a location that is known for Netlogo. When Netlogo is coupled to for example Python, Python searches for libraries at a different location.

Storage of variables The following information are important when models are coupled:

- What does the model need? (input)
- What does the model give (output)
- Where are variables stored?
- At what time does communication take place?

I may occur that a variable is not stored at the right place, and that a coupled model retrieves the data from the wrong place (an 'old variable').

Debugging When models are coupled it is sometimes difficult to see where an error occurs. Not all formalism can display the errors from another formalism in the correct way.

Appendix G: Correlation between model outcomes

Some hypothesis about correlation between model outcomes are tested. The outcomes will be analysed and a suggestion will be made about whether this relation is expected to be causal or correlated. If the hypothesis about a particular correlation is confirmed, this correlation should be taken into account during the analysis of the results, when the results are interpreted.

Since the business value of PoRA is an overall measure of the performance of the port area, the correlation between the other main outcomes and this outcome are plotted against each other. Several hypothesis will be tested.

Hypothesis 1
When the occupancy of the terminals increases, this will have a positive effect on the business value of PoRA.

Hypothesis 1 is confirmed. Pearson=0.83, p=0 (significant)

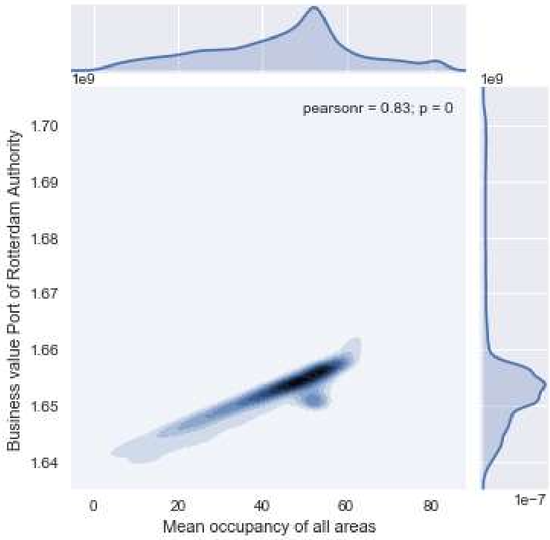


Figure 62: Hypothesis 1

Hypothesis 2
When the coal throughput to Rotterdam increases, the denied throughput based on the infrastructural capacity also increases.

Hypothesis 2 is confirmed. Pearson=0.97, p=0 (significant)

When the throughput and the denied cap are strongly correlated, this suggests that the current infrastructural capacity is not large enough to process all throughput. This could be a signal for PoRA to undertake actions.

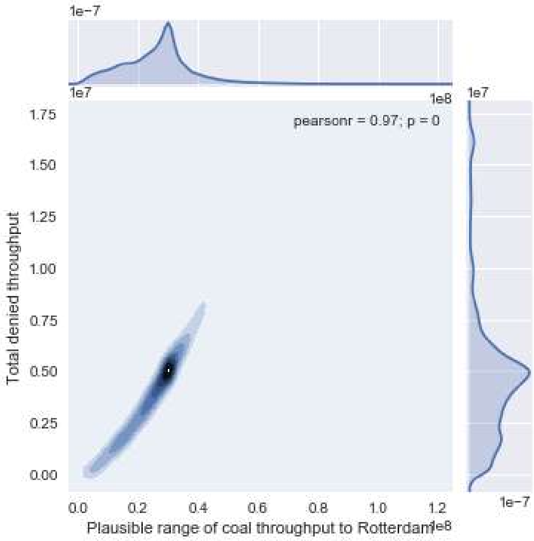


Figure 63: Hypothesis 2

Hypothesis 3
When the infrastructural capacity of the port area is not large enough for the expected throughput to the port area and throughput is denied based on the infrastructural capacity, this has a negative impact on the business value of PoRA.

Hypothesis 3 is confirmed. Pearson=0.94, p=0

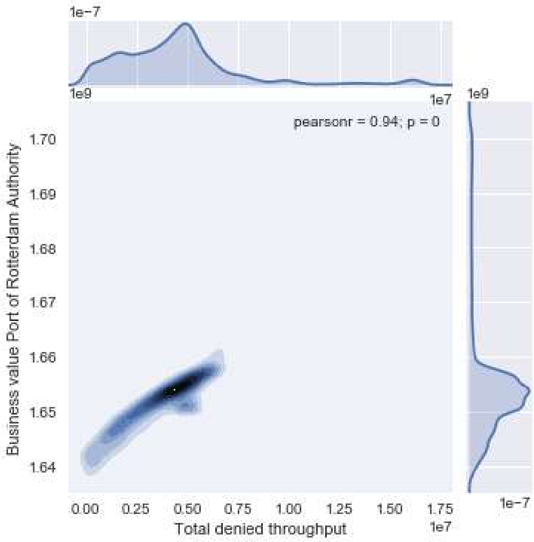


Figure 64: Hypothesis 3

Appendix H: PRIM analysis

An example of the results of a PRIM analysis is shown in Figure 66. The most left and right numbers indicate the full range for each of the uncertain factors. The blue bars indicate the uncertainty subspaces that are identified by PRIM. The number between brackets is the quasi-p value, which indicate whether the subspace is significant or not (Halim, Kwakkel, & Tavasszy, 2016b). The PRIM analysis is performed four the four different paths.

Monotonically increasing

In this case, the outcomes of interests are those where the path of the model outcome does not change direction, and where it increases monotonically. The following classification rule is applied:

$$ratio\ of\ variation \leq 1.05 \quad and \quad TP_{t=1} < \ TP_{t=2}$$

Outcome: 219 cases of interest

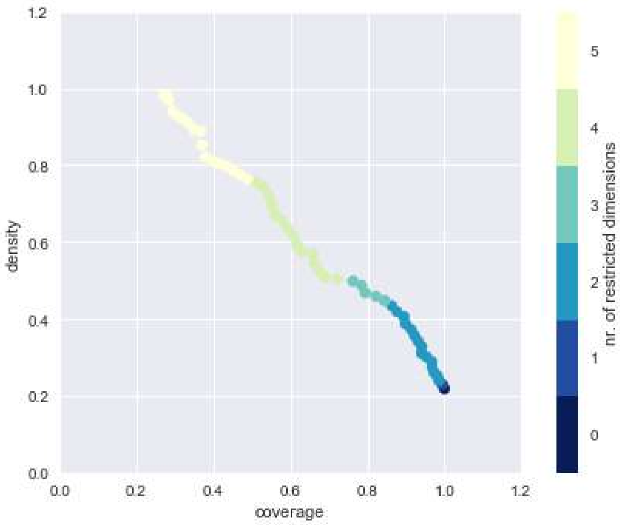


Figure 65: Trade-off PRIM analysis (monotonically increasing)

Figure 66 shows that 50% of the cases with a monotonically increasing path, can be explained by the combination of four uncertain factors.

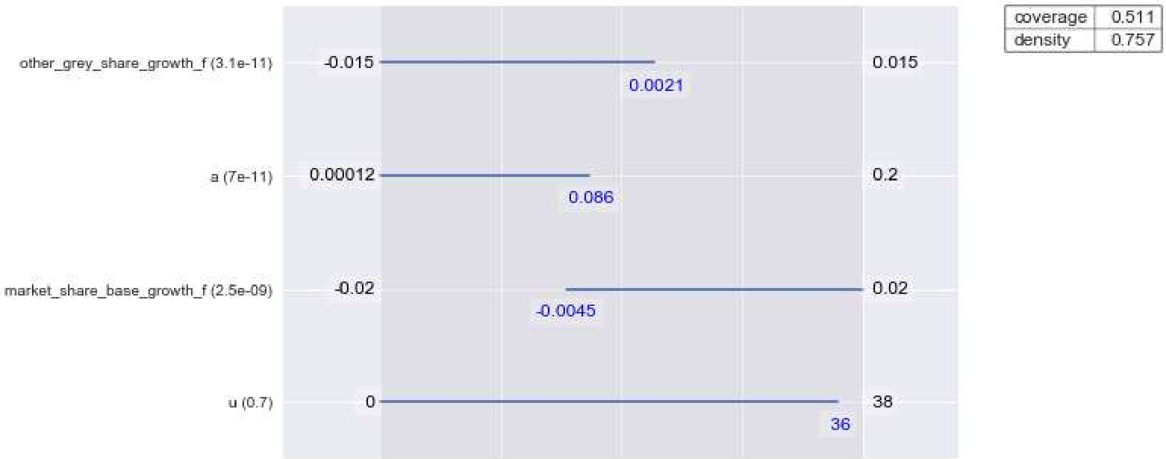


Figure 66: PRIM outcome (monotonically increasing)

The following statements can be made:

- The share of other grey energy sources decreases, or increases only a little bit.
- The energy transition takes place at a low pace.
- The market share of Rotterdam increases.

Monotonically decreasing

In this case, the outcomes of interests are those where the path of the model outcome does not change direction, and where it decreases monotonically. The following classification rule is applied:

$$ratio\ of\ variation \leq 1.05 \quad and \quad TP_{t=1} < \ TP_{t=2}$$

Outcomes: 524 cases of interest.

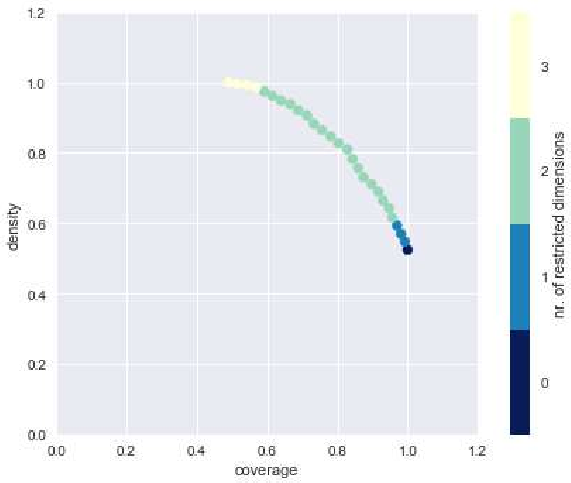


Figure 67: Trade-off PRIM analysis (monotonically decreasing)

Figure 68 shows that 49% of the cases with a monotonically decreasing path, can be explained by the combination of three uncertain factors.

Figure 68: PRIM outcome (monotonically decreasing)

The following statements can be made:

- o The market share of Rotterdam will decrease the coming 40 years.
- o The share of other grey energy sources increases.

Non-monotone, starting with a decrease

In this case, the outcomes of interests are those where the path of the model outcome changes direction at a certain moment in time and where the path starts with a decrease. The following classification rule is applied:

$$ratio\ of\ variation \geq 1.05 \quad and \quad TP_{t=1} > \ TP_{t=2}$$

Outcomes: 77 cases of interest. Not meeting the threshold. This means that the chance that this path occurs is not high, and that there is no specific range of combinations of uncertainty that explain this path.

Non-monotone , starting with an increase

In this case, the outcomes of interests are those where the path of the model outcome changes direction at a certain moment in time and where the path starts with an increase. The following classification rule is applied:

$$ratio\ of\ variation \geq 1.05 \quad and \quad TP_{t=1} < \ TP_{t=2}$$

Outcomes: 180 cases of interest.

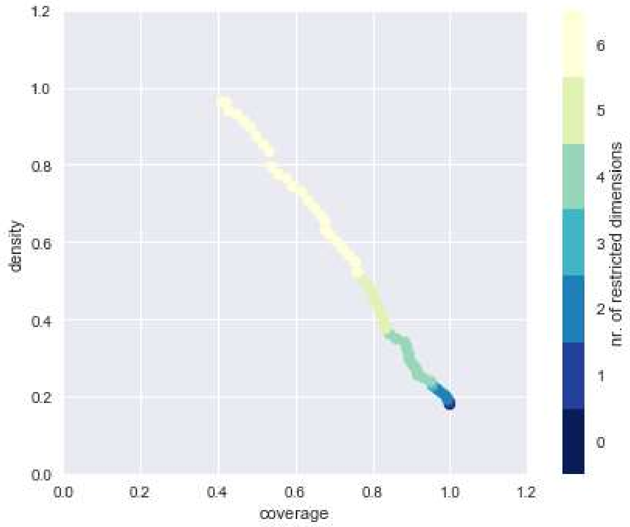


Figure 69: Trade-off PRIM analysis (non-monotone, starting with an increase)

Figure 70 shows that 87.9% of the cases with a non-monotone path, starting with an increase, can be explained by the combination of five uncertain factors.

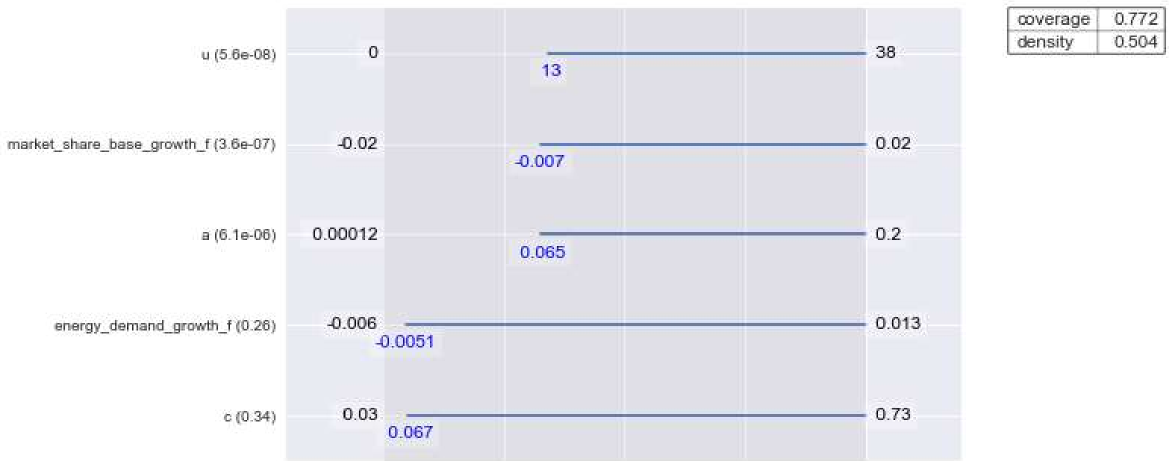


Figure 70: PRIM outcome (non-monotone, starting with an increase)

The following statements can be made:

- The energy transition does not start earlier than in 2030.
- When the transition start, the speed of this transitions is high.
- The market share of Rotterdam keeps increasing the coming years.

Appendix I: Expert consultation interviews

1. Wat is naar jouw mening het grootste verschil met de huidige werkwijze?
2. Wat denk je te kunnen doen met dit model van ecosystemen wat met de huidige modellen niet kan?
3. Wat kan er verbeterd worden aan het ontwerp?
4. Is het haalbaar om een dergelijk model ecosysteem te implementeren?
5. Wat is er nodig om een model ecosysteem zoals in dit ontwerp te implementeren bij de haven?
    a. Geld?
    b. Mind-set?
    c. Kennis?
6. Stel dat een dergelijk model ecosysteem wordt geïmplementeerd, hoe zie jij je eigen rol dan in het proces?

Vertaling naar andere goederen soorten

1. Is het proces rond alle goederen soorten ongeveer hetzelfde?
2. Zijn het dezelfde type beslissingen die worden genomen?
3. Zo nee, waar verschillen deze beslissingen het meest?
4. Zou het mogelijk zijn om dit ontwerp ook toe te passen voor de andere goederen soorten?

Appendix J: Scientific article

A model ecosystem to support decision-making under deep uncertainty: a case study on the Port of Rotterdam Authority

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Abstract

The environment is changing continuously and the uncertainty that large organisations are facing is getting higher. It is hard for these organisations to make reliable statements about plausible futures. This unpredictable and uncertain future complicates the decision-making process of these organisations. A case study is presented for the development of a model ecosystem for the Port of Rotterdam Authority. This model ecosystem consists of various coupled components. By applying Exploratory Modelling and Analysis in combination with a model ecosystem, organisations are able to explore the impact of changes throughout the entire decision-making process chain. By applying scenario discovery, it enables organisations to explore which underlying uncertainties cause particular future paths. With a model, ecosystem organisations are armed with a set of tools to address the challenges encountered in their decision-making process. The model ecosystem dams the future and can reduce the uncertainty space. By reducing this uncertainty space, a model ecosystem enables organisations to make no-regret decisions, which make them more resilient.

Keywords: model ecosystem, deep uncertainty, Exploratory Modelling and Analysis, decision-making, infrastructure system

1. Introduction

Organisations that are responsible for large infrastructures, often serving a public function, are subjected to economies of scale (natural monopoly characteristics) and are often privately owned, are named in literature as 'infrastructure systems' (Ouyang, 2013). Examples of these types of organisations are: seaport authorities, airports, TSOs and rail network managers. These organisations are part of a complex system which is often set to the limits of their spatial boundaries, and the number of stakeholders involved is high (Verbraeck & Valentin, 2002). Their decisions have economic, environmental and social impacts (Van Wee, 2007). These characteristics make them part of a socio-technical system, an interlinked, systems-based mixture of people, technology, and their environment. These systems are often subjected to a lot of changes and a high degree of uncertainty exists (Kwakkel, Walker, & Haasnoot, 2016). Examples of these changes are the unstable world trade due to the economic crisis, the energy transition, globalisation, liberalisation and stricter environmental limits (Taneja et al., 2011). The decisions made by these organisations are characterised by their large size, complexity, high costs and long-duration (Hallegatte et al., 2012). Besides the characteristics of the system and the decision, the large variety of stakeholders may all have a personal point of view regarding these uncertainties and regarding the decision-making process, and decisions are made under deep uncertainty (Kwakkel et al., 2013). This large variety of actors, continuously changing environment and increasing (deep) uncertainty complicate their decision-making process. These organisations struggle with making sustainable and resilient decisions (Lounis & Mcallister, 2016).

1.1. Methodology

One way to systematically explore the uncertainties within a system is by using simulation models (Fujimoto, 2017). These simulation models should represent the dynamics of the system and give the possibility to explore a large variety of possible future scenarios. These systems in its entirety are becoming too complex and the environment is too uncertain to capture the entire system in one simulation model (Yilmaz et al., 2007). A suitable approach to solve this problem is by developing a model ecosystem, which is a multi-model system in which multiple models interact with one another (Bollinger et al., 2015). In this approach, the focus does not only lie on technical characteristics of the system, but the system is more approached as a socio-technical system. A model ecosystem can be used to support organisation in managing the interaction with the large variety of stakeholders more systematically and to oversee the socio-technical consequences of uncertainties on the strategic and operational decisions.

In order to demonstrate how a model ecosystem approach can support organisations in their decision-making process, an illustrative case study is presented. In this case study, the way a model ecosystem can support the Port of Rotterdam Authority (PoRA) in their decision-making process, is assessed. This paper demonstrates how theoretical model ecosystem approaches translate to real-world business. The case study consists of three steps: the design of a model ecosystem, the implementation of a proof of concept of this design and the analysis of the results of the proof of concept.

1.2. Structure

Section 2 starts with an explanation of the model ecosystem that is developed for PoRA. After which a brief explanation of the implementation of the proof of concept is given. In Section 3, it is discussed how the uncertainties could be best approached, using Exploratory Modelling and Analysis. In Section 4 an application of EMA, scenario discovery, is applied to the model ecosystem. The article concludes with the discussion and a conclusion.

2. The design and implementation of a model ecosystem

The first step in the design of a model ecosystem is the analysis of the current decision-making process. Before this analysis can start, the scope of the model ecosystem needs to be defined. This scope illustrates what the exact 'decision-making process' is that needs to be supported. After that, the current decision-making process needs to be analysed and a clear process diagram needs to be developed. This is an important, but complex step. Mapping the system requires a lot of effort, often there is no unambiguous decision-making process, people perform small side steps, which are not known by everyone and not everybody is involved in the entire decision-making process.

Based on the current decision-making process of PoRA, the model ecosystem designed for PoRA consists of five components. Every component stands for one element within the decision-making process. The design is shown in figure 1. The most important characteristics of this design are the modularity, the use of automated tools, the coupling between the various components and the strict definition of in and outputs of the components. Because the design consists of a modular system, in which the different components can be adjusted or replaced, it allows PoRA to improve, adjust or expand the existing models by the experts who have the most knowledge about these components. The use of automated tools enables PoRA to explore a wide range of plausible futures. The coupling of the various components ensures that one coherent, ecosystem of models is created. At every place in the ecosystem changes can occur and these changes can have an impact on the different components. Because the various components are coupled, the impact on the ecosystem following a change in one of the components of the ecosystem can be assessed.

For the development of the proof of concept, it is chosen to use a master through which the components communicate. This master can be compared with the RTI in the HLA (Fujimoto, 2000). The master synchronizes, controls and manages the different components (Bastian et al., 2011). This master-component allows communication between the models and data exchange between the models takes place.

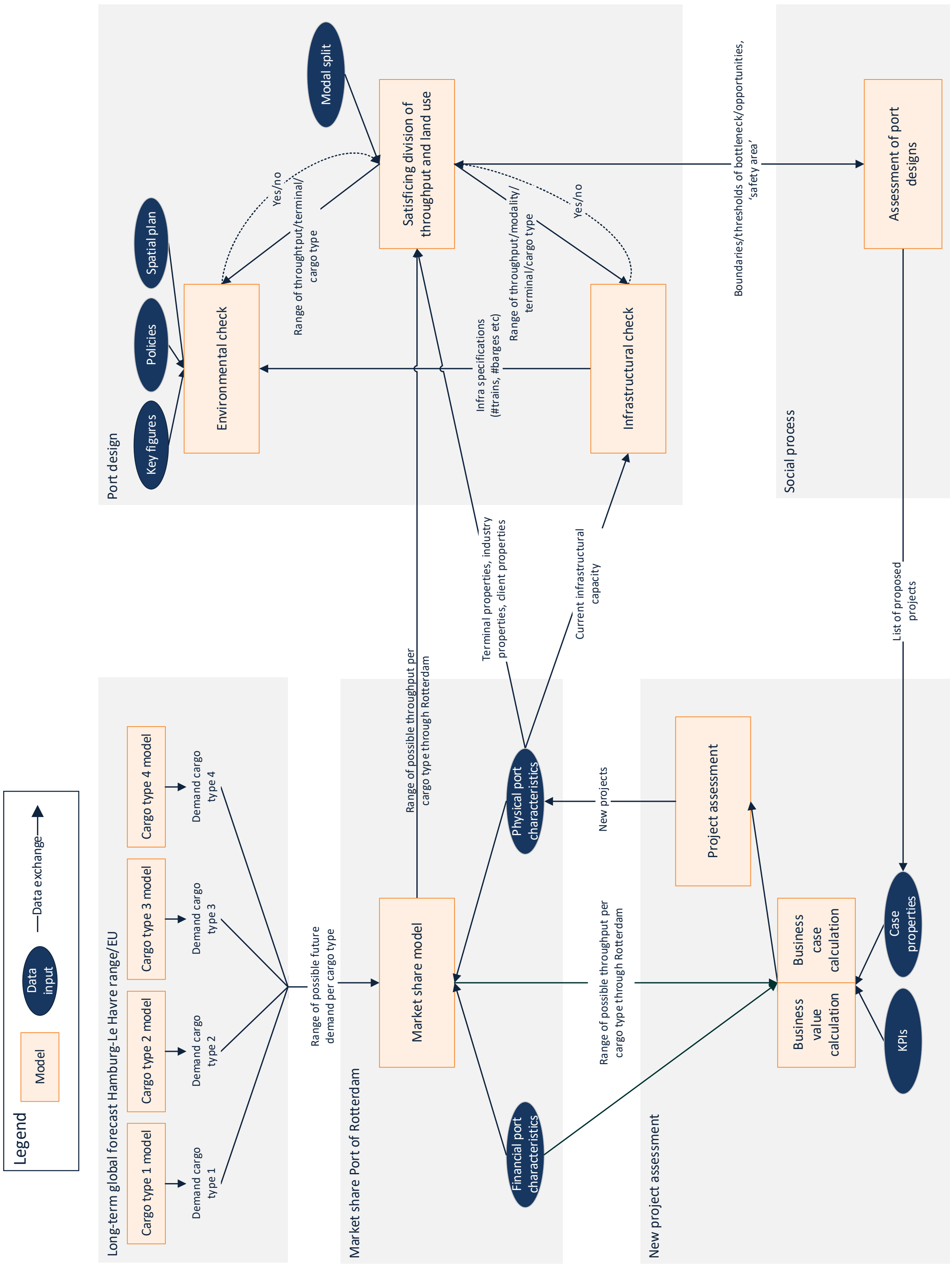

Fig. 1. Design of a model ecosystem for PoRA

3. The analysis of the results of the proof of concept

A model ecosystem enables PoRA to explore the uncertainties in a systematic way. In order to do so, Exploratory Modelling and Analysis (EMA) is applied. By applying EMA to the model ecosystem, new capabilities become available to explore the uncertainties that PoRA is facing. EMA enables PoRA to explore the full range of plausible future and to assess the impact of changes on the system (Kwakkel & Pruyt, 2013). It allows them to gain insights in the bandwidth of the outcomes of the models given the range of plausible futures. By using scenario development, PoRA is also able to develop narratives that describe the various uncertainty subspaces in which different types of future paths are grouped. It gives insights in the uncertainty subspaces that lead to particular (desirable or undesirable) outcomes. These subspaces can be translated to *communicable, internally consistent, and plausible narratives* (Greeven et al., 2016). An example of one of the outcomes is given in Figure 2.

In this figure, the uncertainty space of the coal throughput to the port area is shown. The conclusion that can be drawn from this figure is that the uncertainty space of this model outcome, given the full range of uncertainties, is very large. This is consistent with the existence of deep uncertainty within the system of the port area. A second observation is that the range of model outcomes gets wider further in time. This is caused by the fact that the uncertainties accumulate over time, which make the far future even more unpredictable than the near future.

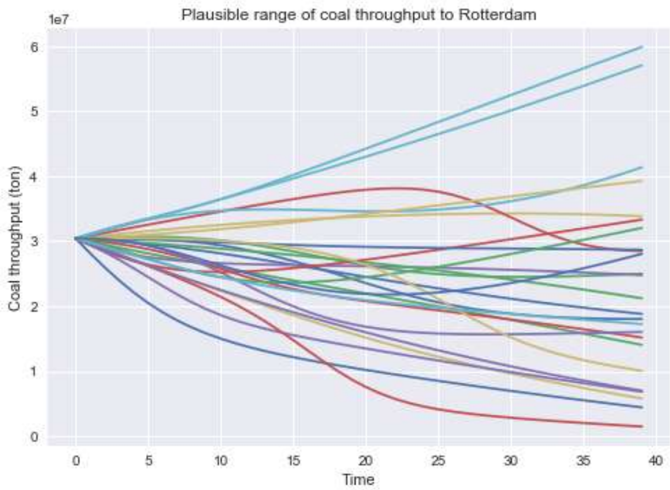

Fig. 2. Plausible range of coal throughput to Rotterdam

A third observation is that different types of future paths can occur. Two types of paths are defined: the monotonous paths and the non-monotonous paths. When the path is monotonous, the path either increases or decreases over time. Due to the deep uncertainty, it is hard to predict how much growth or decline there will be, but for PoRA this will be less 'dangerous'. If it is known, beforehand, that the coal throughput will monotonously increase or decrease in the coming 40 years, PoRA can respond to this by either closing terminals or attracting new businesses within this cargo type. When the path is non-monotonous, the path changes direction during the coming 40 years. When the path increases the first 15 years, it might seem as if everything is going well – but then, suddenly, it turns around.

As mentioned before, the decisions made by organisations like PoRA are often characterised by their large size and long duration and often associated with high costs. It is, therefore, not possible for PoRA to attract new customers in the first five years and change their strategy in the coming 5 years. It is important to know what types of paths can be expected, as a different type of path asks for a different approach. For PoRA it is, therefore, of great importance to know which subspaces provide a particular type of path. They need to know how stable the twists are, and if the fluctuations only occur with a very specific combination of uncertainty parameters, or with a wide range of parameters. And how often do these combinations occur? How likely is it that these combinations of uncertainty parameters occur, and how stable are these subspaces? Because, then, you should really take these paths into account. On the other hand, PoRA also needs to know which uncertainty subspaces provide non-monotonous paths.

4. Scenario discovery

Scenario discovery is an application of EMA that enables one to search for these particular subspaces within the uncertainty space (Kwakkel & Jaxa-Rozen, 2016). When scenario discovery is applied for this purpose, several subspaces within the uncertainty space are determined. These subspaces can be translated to *communicable, internally consistent, and plausible narratives* (Greeven et al., 2016). PRIM is an algorithm frequently used for scenario discovery. With PRIM, the underlying uncertainty parameters are found, of the uncertainty subspaces that lead to similar model output. PRIM divides the uncertainty space into boxes and searches for the box with the highest density and the highest coverage. The coverage answers the question: of all the cases of interest, how many are situated within this box (Bryant & Lempert, 2009). The density covers: of all cases in the box, how many are of interest? This PRIM analysis enables PoRA to make no-regret decisions.

4.1. No-regret decision

No model can ever predict the exact future, but a model ecosystem can explore the possible futures. The model ecosystem allows PoRA to see what can be expected. Are there any options that always have a favourable outcome - or always have an outcome that is disadvantageous? It gives PoRA insights in the no-regret options. What should they do in each case? And what should they never do? No-regret decisions are decisions that can be justified from economic, social, and environmental perspectives – whether large changes take place or not. The ability to discover what the no-regret decisions are, reduces and delimits the uncertainty space and they increase the resilience of PoRA. This means that PoRA will be better-prepared for possible risks or changes within the environment and can protect themselves against them (or at least try to). This no-regret decision is demonstrated by means of an example.

4.2. Example

PoRA wants to assess a new proposed project. This project concerns the attraction of a new client, who wants to establish within the port area with a new terminal. To assess the contribution of this new terminal to their KPIs, the new terminal will be inserted in the model ecosystem. The performance of the port with the new terminal will be assessed. The following criteria are taken into account in this assessment: the total throughput to the area, the total throughput to Rotterdam (if the terminal does not achieve an increase of the total throughput to Rotterdam, the terminal would only cause a shift of throughput from one to another terminal). In Figure 3, the results of the PRIM analysis are shown.

This figure shows that there are five uncertainties that are highly predictive for a positive assessment of the project, of which four are significant. These uncertainties are all sampled from a uniform distribution. In reality, not all uncertainties have a uniform distribution and it is not true that the distribution of uncertainties is completely unknown. This causes the fact that some combinations of uncertainties that are sampled are not realistic. Therefore, PoRA needs to decide how plausible they consider these combinations of uncertainties. Figure 4 shows the paths of throughputs for Rotterdam, which are predictive for a positive assessment of the project. This figure demonstrates that only if the throughput increases the coming years, the project terminal will be profitable.

Fig. 3. PRIM analysis results

During a validation session with PoRA experts, these results are discussed. All respondents agree upon the fact that the combinations of assumptions about the uncertainties, leading to the positive assessment of the terminal, are not plausible. This means that the terminal will only be profitable in a future that is not realistic. That means that PoRA should, whatever future may occur, refrain from building this terminal. This example may be not realistic, as it is highly unlikely that a new coal terminal will be built. However, this example does demonstrate how a model ecosystem can support PoRA in making no-regret decisions.

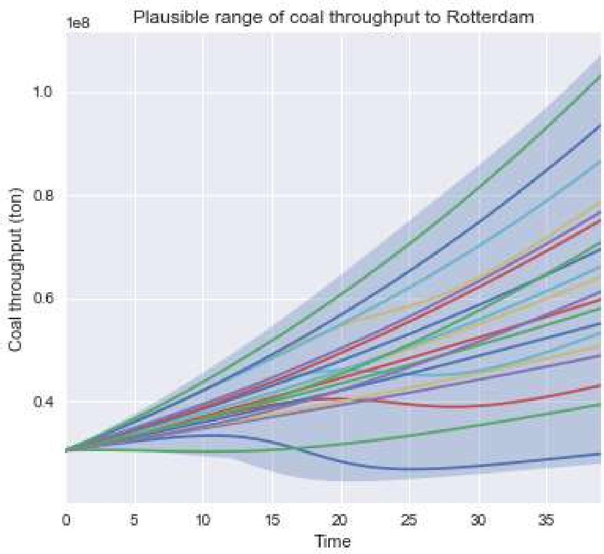

Fig. 4. Combination of uncertainties

4.3. Impact on the decisions

In the decisions currently made, all the accumulated knowledge is already implicitly taken into consideration. Because this same knowledge will be used to develop the models, it is expected that the outcome of the decision will not have changed. The model should, therefore, lead to the same conclusion as human choices. The model ecosystem, however, can be reinforcing. When the outcomes of the model are the same as the expectations of the employee, the expectations are confirmed. But not only are the expectations confirmed, it can also become clear why something happens. This can strengthen the decision.

By using a model ecosystem, one gets a clearer idea regarding why and on what grounds particular decisions are made, and which uncertainties are taken into account. Better estimations can be made and you will get rid of the: 'let's just do this'. Decisions will be better substantiated, deliberated, and informed by a model ecosystem. This makes it easier to justify particular decisions. Eventually, the decisions will get 'better'. Not the go-or-no-go for a particular decision, but especially after the decision has been made. One will know better what to expect and what to look out for. It, also, allows PoRA to steer the decision later in the process.

5. Discussion

What becomes clear is the importance for organisations to focus on the interpretation of the meaning of the output of a model ecosystem. Regardless of the form and content of the model ecosystem, what can organisations say about the future based on these types of outcomes? What does it mean that the uncertainty space is that large? It means that it is hard to predict 'the' future and that they should focus on the types of future paths that exist. The insights about the plausible future paths enable organisations to develop a strategy that is capable to withstand the uncertain and unpredictable future. Even if a model ecosystem is not based on real data, and consists of simplified models, one can still explore what types of future paths exist. Through this way of using models, the focus shifts from emphasizing on the right data and developing as detailed models as possible, to focusing on what types of futures may occur and in what way an organisation can adjust their strategy to meet their objectives. This is in line with authors who write about the more explorative use of models. Like Kwakkel & Pruyt (2013) state, by using models in a more explorative way, one can gain a lot of information from the model ecosystem, even when the exact data about the system is not completely known and the models do not contain all the details of the system. Because a wide range of plausible futures is explored, the way in which these plausible futures have come about is less relevant.

6. Conclusion

When organisations make decisions under deep uncertainty, a model ecosystem can support them by approaching the uncertainties in a systematic way. With a model ecosystem, organisations are armed with a set of tools to address the challenges encountered in their decision-making process, both the practical challenges and the challenges regarding the deep uncertainty. It eases the decision-making process because the system is approached in a more integrated manner. Through the use of a model ecosystem, organisations can assess what the impact changes within the environment have on the system. By applying EMA to organisations, new capabilities to explore uncertainties become available. It enables PoRA to approach the uncertainties in a systematic way. They are able to explore a wide range of plausible futures and discover which future paths may occur. By using scenario development, organisations are able to develop narratives that describe the various uncertainty subspaces in which different types of future paths are grouped. It gives insights in the uncertainty subspaces that lead to particular (desirable or undesirable) outcomes. The decision itself may not always change, but the process of making this decision will be different. Decisions will be better substantiated, deliberated, and informed by a model ecosystem. This makes it easier to justify particular decisions. The model ecosystem dams the future and can reduce the uncertainty space. By reducing this uncertainty space, a model ecosystem enables organisations to make no-regret decisions, which make them more resilient.

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