Designing a Multi-Model Ecology for Dutch drinking water utilities

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Designing a Multi-Model Ecology for Dutch drinking water utilities

by

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for Frans and Trudy

Preface

'Toto, I've a feeling we're not in Kansas anymore.'
Dorothy

When I was much younger, my parents gave me a cassette player for my birthday, at that time the state-of-the-art. Due to my inquisitive nature, I decided -at some point- to explore its inner workings and to disassemble the cassette player. Unfortunately, it proved very challenging to reassemble the device much to my parents' dismay. I think this partly explains my fascination with (simulation) models and modelling. Here, we have a technique that lets us explore the inner workings of a system without having to break it. Having learned from that experience, my inquisitive nature eventually led me to TU Delft many years later. A decision I have not regretted since the TU experience has changed me and my life in such a positive way.

Dear Frances, when I started the CoSEM master's program after my bachelor's degree in Architecture, I was very impressed by the skills of my fellow students. I had then done a minor to be admitted to the CoSEM master's degree, and I somewhat regretted that I had not been able to do the entire TB bachelor's degree. Thanks to your lectures and our conversations about the importance of understanding design processes, I realized that I may not have known everything about the TB bachelor's degree, but that I had my own experience that others did not have at the time. After that, I followed the course on Participatory Design. Which gave me the idea that I am able to design a suitable solution for every challenge. The recent period has been very challenging on several levels. However, I look back with great pleasure on your personal involvement and support. Thank you!

Dear Igor, thanks to your courses I have learned, among other things, about the concept of worldview, which simultaneously changed my worldview. Thank you for that and other insights. But you also taught me how to model with stakeholders, which is how I ended up at Oasen via KWR. Which not only changes to my worldview, but now my entire life. I greatly appreciate the way in which you can instantly get to the heart of a problem. And just as quickly to a solution. I really benefited from our conversations about multi-modelling and all the critical feedback on my research.

Dear Petra, I would like to thank you, particularly for your critical approach to my thesis topic. It challenged me throughout this project to pay attention to the necessity, merit and appropriate application of an MME. In addition, in our first meeting, you helped me realize that I was drowning in opportunities. That insight was very helpful throughout my thesis project. Since there was plenty more opportunity to drown in further down the line.

Mirjam Blokker, I remember very well when Maarten and I were working on the ABM model for KWR when we realized that we were designing a system (a water system) without any knowledge of it. Our only option to solve that quickly was to engage you, Ina and Peter to provide us with insights. What all three of you loved to do. I also gratefully made use of your wealth of experience during this research. You also helped me a lot by reminding me to focus and to keep thinking about the implications of this research for Oasen and the drinking water sector.

Ina Verstommen (KWR), thank you for all your thoughts and your pragmatic solutions for all the hurdles that had to be overcome during this research. I greatly appreciate all the feedback and input you have given me during this research, but also for your involvement.

Robert Schoofs (Oasen), thank you for believing in the added value of a multi-model ecology for Oasen and all the support I have received to complete this research.

I would also like to thank my colleagues at Oasen for all their enthusiastic responses to my graduation topic and their support. Especially the colleagues I had the pleassure to interview about the use of models at Oasen: Irene Caltran, Jos den Boon, Jan Willem van Egmond, Morez Jafari, Guido Kersten, Menno van Leenen, Geert Luijkx, Maarten Lut, Rosa Sjerps, Michele Stefani, Fabiaan Zaat and Piet Vermeulen. In addition, I would like to thank Toan Nguyen and Ljiljana Zlatonovic from Oasen for all the work on developing an EPANET model for this research. Without a small model, I would probably still be busy right now! Ljiljana, thank you also for proofreading parts of this thesis report.

I would also like to thank my family and friends for all the support during my studies, each in his or her own capacity. Especially my mother Trudy, my sister Linda, brother-in-law Robert and all of the children and my father-in-law Puck. I would also like to mention my aunt Tineke Thielemans who unfortunately passed away earlier this year. She was a big fan and outspokenly proud of my determination to successfully complete my studies at TU Delft.

Finally, to my husband Michael, thank you for your support, faith and patience during all the time it took me to complete this study. Sometimes, I think you believed in it even more than I did at times. We both have gained a lot from this experience. Especially in the beginning when I could relate so much of what I learned to the experiences you had in your work. Finally, then it is done! We did it together. Thank you with all my heart.

Enjoy the read!

B.F. Luttikhuizen
Delft, January 2024

Executive Summary

The main problem that this research seeks to address is a lack of engagement with stakeholders of drinking water utilities in the decision-making processes of the drinking water utilities. A way to engage with stakeholders is by using Participatory Modelling, a technique that is not commonly applied by drinking water utilities to engage with stakeholders for better decision-making. Continuing to supply drinking water for the long term is coming under pressure from challenges on the supply side, related to water quality and quantity on the one hand and developments due to increasing demand for drinking water on the other. Both developments are expected to be negatively influenced by the effects of climate change. However, to what extent is currently unknown. Despite a lack of insight into future developments, drinking water companies must make strategic investment decisions to meet the future demand for drinking water. The Dutch drinking water companies face three major challenges regarding strategic investment decisions. First, the current sourcing and production capacity must be expanded to meet future drinking water demand. This results from an expected population growth, possibly in combination with higher drinking water consumption from residential customers and businesses. Second, there is a great demand for End-of-Life replacement of pipes in the drinking water infrastructure. These infrastructures were often built after WWII and are reaching the end of their lifespan. They must be replaced before they either leak or break and cause outages. This End-of-Life replacement task requires significant investments. Third, an investment challenge of a lesser financial magnitude but with an expected great impact on business operations is related to gaining operational control over the drinking water distribution network by integrating state-of-the-art sensor technology. And developing reporting or visualisation software tools such as dashboards or Digital Twins to relay the operational status of the network to its operators. The working principle of drinking water distribution systems hasn't changed since their first application in the 19th century. Still, their complexity has increased due to growing customer connections and changing demand patterns. Traditional water distribution systems operate as a black box, whereas contemporary distribution systems equipped with sensor technology offer (near) real-time insights for business operations. The outcomes of the internal decision-making processes of the drinking water utilities regarding these three strategic challenges will affect the stakeholders of the drinking water utilities. In addition, it offers possibilities for alignment with the goals of the other stakeholders. These possibilities for alignment are further backed by the development of new resources that have become available in recent years. These resources are on the one hand, new modelling techniques that have been applied in the field of drinking water research. And a novel perspective on multi-modelling e.g. the Multi-Model Ecology (MME) with Multi-Model Interface (MMI). In the current practice of research for Water Resource Management and other research for drinking water utilities, an MME and MMI (MME+I) have not yet materialised.

The aim of this study is to determine if an MME+I can benefit research for drinking water utilities. In addition, can it be useful as a tool to support Participatory Modelling to involve stakeholders in the decision-making process of drinking water utilities? To answer these two questions, both a MME and a MMI are needed. Since these do not yet exist, they must be designed and prototyped. The sub-research questions are structured to support the design of an MME+I specifically for drinking water utilities while using existing knowledge and experiences of operational MME+Is from other research fields. The main research question is:

How can a multi-model ecology aid the design of a future-proof drinking water distribution system?

The research objectives involve performing a Literature Review on the design requirements for an MME to apply existing knowledge and experiences of operational MME+Is. In addition, semi-structured interviews were held to solicit an overview of commonly applied models used at Oasen and relevant stakeholders. This has been done in order to align the functionality of the design of the MME+I to the resources available at Oasen and relevant stakeholders. The third research objective concerns the design of an MME+I. This results in a design for a conceptual model of the MME+I and a logical architecture for the MMI. The fourth and final research objective is a multi-modelling Proof of Concept

use case.

The main method applied in this thesis to deliver the design of an MME+I and a Proof of Concept (PoC) are generated through an established Design Science approach. The Participatory Systems Design (PSD) approach was chosen for the MME design.

The design artefacts consist of a design for the MME and MMI. Where the MME is presented as a conceptual model. For the design of the MMI, a Logical Architecture is presented. The Proof of Concept use case strategy is designed with the XLRM framework.

The Proof of Concept use case consists of a multi-modelling approach through model-coupling (see Figure 1). An ABM model for Water Demand is used to generate water demand patterns for an EPANET hydraulic model. This is a novel approach in hydraulic modelling for Oasen since it introduces agents' behaviour from the ABM model to the modelling of hydraulic networks. Where generating water demand patterns through stochastic modelling is the established method.

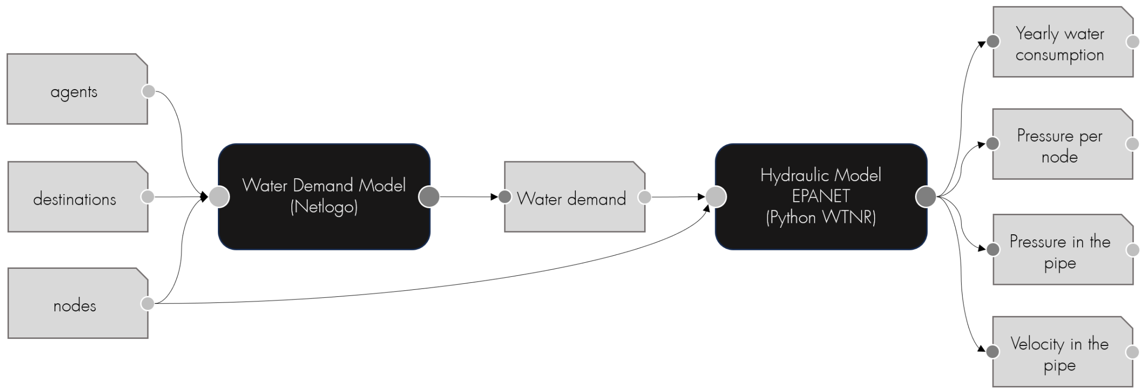

Figure 1: Proof of Concept Multi-modelling Strategy

The main limitations of this thesis research into an MME+I for the Dutch drinking water utilities is that the design process for this Participatory System took place without involving all of the stakeholders. However, the greatest limitation is also the greatest strength of this study. Using the PSD methodology, it is possible to generate a design for an MME+I for Oasen and the drinking water utilities with significantly fewer dedicated man-hours. Another limitation of this thesis research is that it is a design process. Although the design process is documented step by step in this thesis, it is not replicable. Another limitation comes from the method of using a participatory design process with a designer. In a participatory design process with solely a designer interacting with stakeholders without stakeholders interacting among themselves, there is no shared vocabulary from a social process. In addition, issues relating to the authority of the process or its outcomes are also not addressed.

The main research question is "How can a multi-model ecology aid the design of a future-proof drinking water distribution system?"

In this thesis research, an MME+I was designed and implemented in a PoC use case for multi-modelling and demonstrated that the outcomes of an ABM-model affect the EPANET hydraulic model's performance. It provided insight into how changes in water demand from scenario studies can affect strategic investment decisions for drinking water utilities. In addition, this research has yielded the following results:

- A method for Model Assessment to acquire model meta-data.
- Displayed a knowledge gap on design considerations and alternative selection for operational MMEs.
- Presented the design characteristics for operational MMEs.
- Presented the design requirements for an MME.
- Presented the design requirement and logical Architecture for an MMI.

- Presented an overview of relevant developments on data and modelling for the Ducth drinking water sector.
- Coupled an ABM model to an EPANET hydraulic model

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Nomenclature

Abbreviations

Abbreviation	Definition
ABM	Agent-based Modelling
CML	Customers Minutes Lost
DWDS	Drinking Water Distribution System
GUI	Graphical User Interface
MME	Multi-Model Ecology
MME+I	Multi-Model Ecology with an Multi-Model Interface
MMI	Multi-Model Interface
NRW	Non Revenue Water
PM	Participatory Modelling
PSDM	Participatory Systems Design Methodology
PoC	Proof of Concept
SDLC	Software Development Life Cycle
SRE	Software Requirements Engineering
WRM	Water Resource Management

“You never fail until you stop trying.”

Albert Einstein

1
Introduction

1.1. Challenges for the drinking water sector

Access to drinking water and sanitation is defined by the United Nations as a human right (Luh et al., 2013). Urban water infrastructures provide essential services to modern societies. Access to high levels of drinking water and wastewater services is fundamental for protecting public health, the population's comfort and well-being, the community's sustainable development and environmental protection (Meier et al., 2013).

In the Netherlands, 10 drinking water companies are public utilities responsible by law for providing high-quality drinking water to their geographically assigned customer base. Continuing to supply drinking water for the long term is coming under pressure from challenges on the supply side, related to water quality and quantity (Birkenholtz, 2016; Van Steen & Pellenbarg, 2004) on the one hand and developments due to increasing demand for drinking water on the other (Kloosterman & Van der Hoek, 2020). Both developments are expected to be negatively influenced by the effects of climate change. However, to what extent is currently unknown (Maiolo et al., 2017). Despite a lack of insight into future developments, drinking water companies must make strategic investment decisions to meet the future demand for drinking water. The Dutch drinking water companies face three major challenges regarding strategic investment decisions. First, the current sourcing and production capacity must be expanded to meet future drinking water demand (IcaStat, 2018). This results from an expected population growth, possibly in combination with higher drinking water consumption from residential and business customers (IcaStat, 2018).

Second, there is a great demand for end-of-life replacement of pipes in the drinking water infrastructure (DWI). These infrastructures were often built after WWII and are reaching the end of their functional lifespan. They must be replaced before they either leak or break and cause outages and collateral damage. This end-of-life replacement task requires significant investments (Selvakumar & Tafuri, 2012). Leaks, breaks and related outages also harm the Key Performance Indicators (KPIs), such as Customers Minutes Lost (CML) and Non-Revenue Water (NRW). CML is the total minutes a year that customers are not supplied with (enough) drinking water due to maintenance of the water distribution network (planned CML) or outages (unplanned CML). Non-Revenue Water is the total amount of drinking water that is produced at the treatment plants but cannot be invoiced to customers of the drinking water company. Replacing and expanding the current drinking water distribution system are interventions with a multiple-year period that require permits and coordination with other parties in the subsurface.

Third, an investment challenge of a lesser financial magnitude but with an expected great impact on business operations is related to gaining operational control over the drinking water distribution network by integrating state-of-the-art sensor technology. And developing reporting or visualisation software tools such as dashboards or Digital Twins to relay the operational status of the network to its operators. The working principle of drinking water distribution systems hasn't changed since their first application in the 19th century. Still, their complexity has increased due to growing customer connections and changing demand patterns. Traditional water distribution systems operate as a black box, whereas contemporary distribution systems equipped with sensor technology offer (near) real-time insights for business operations.

Drinking water companies are part of a complex multi-actor playing field for their above-ground and subsurface assets. Therefore, the outcomes of strategic investment decisions and investment decision processes often require alignment with different stakeholders and the active application of environment or stakeholder management within the company. In this thesis report the Dutch drinking water company Oasen is used as an illustrative example and a use case for this thesis research. Oasen is a drinking water company that supplies drinking water to over 808.160 customers and 3.400 businesses in 21 municipalities in South-Holland. Oasen has above-ground and subsurface infrastructural assets that contribute to the company's primary objective of providing high-quality drinking water to its customers (Oasen, 2022).

Examples of stakeholders are the 21 municipalities that fulfil their institutional role as shareholders of Oasen. However, these municipalities are also responsible for grating permits for building activities such as those needed to realise new purification plants. In addition, the province of South-Holland is responsible for issuing water extraction permits. Further examples include other parties with assets in the subsurface and many others that influence the decision-making and operations of drinking water companies.

Given this external environment and the characteristics (of networks) as defined by (de Bruijn & ten Heuvelhof, 2008) it can be concluded that drinking water companies operate in an (external) multi-actor network. This then implies that for a (drinking water) company to operate successfully, "it should serve not only the interests of its shareholders but also those of the main stakeholders, whose interests might differ from those of the company", Clark in (de Bruijn & ten Heuvelhof, 2008). Consequently, this raises the question: how to organise multi-beneficial collaborative decision-making in a multi-actor network?

A well-established technique for this is Participatory modelling (PM), an approach combining participatory procedures with modelling techniques, is increasingly recognised as an effective way to assist collective decision-making processes dealing with natural resource management (Barreteau et al., 2007). Furthermore, PM has emerged as a way of decision support and conflict resolution, where stakeholder engagement is organised around the process of systems exploration and modelling (Hämäläinen et al., 2020). Ridder et al, specifically state the suitability of PM as a tool for supporting social learning for Water Resource Management [1] (WRM) (Ridder et al., 2005). However, PM has not yet become a common approach within Water Resource Management. Lavrijssen and Vitez conclude a lack of participation by drinking water consumers, interest groups, consumer organisations and experts (2015). The United Nations Sustainable Development Goals Report argues for enhancing cross-sectoral coordination and cooperation among all stakeholders (Costanza et al., 2016). Finally, Hare provides an overview of the perceived benefits but also concludes that to overcome barriers, at least two conditions need to be met: "(1) there need to be sufficient resources available to water managers to support participatory modelling processes, and (2) there is a large demand for new models to support actual water management decisions" (2011).

Recent developments offer support for new approaches in PM for Water Resource Management by addressing the barriers mentioned by Hare. First, since 2011 new modelling techniques such as Machine Learning, Artificial Intelligence, Neural Networks and Deep Learning have become more mature and have been applied for research in the drinking water industry (Hadjimichael et al., 2016; Li et al., 2021; O'Reilly et al., 2018; Sit et al., 2020). Another development is the advancing insight that all single-use models have limitations and that these need to be addressed (Bollinger & Evins, 2015b). However, by combining the results from models runs from several single-use models each with its formalisms, assumptions and limitations a more balanced insight is possible.

Another development within the field of participatory modelling is the idea of "conceptualising participatory multi-modelling as a process of an evolving boundary object ecology, creating and adapting multiple interacting boundary objects provides a novel perspective that is useful for analysis and design of future participatory multi-modelling processes" (Cuppen et al., 2021).

[1] In this thesis Water Resource Management is defined as the activities of drinking water companies throughout the drinking water chain for the operational management of their sourcing and end-product

Closely related to that notion is the notion of purposely creating a multi-model ecology (MME) as depicted in Figure 1-1. An MME is "an interacting group of models and data set co-evolving with one another within the context of a dynamic socio-technical environment" (Nikolic et al., 2019). An MME uses a multi-model interface (MMI) for communication between the components of the ecology such as models, data, scenarios and algorithms. "A multi-model interface can broadly be defined as encompassing the notions of a software interface (API), a structured data representation, a software daemon and a structured social process" (Nikolic et al., 2019). The concept of an MMI is depicted and explained in Figure 1-2. MMEs and MMIs are concepts that can occur in research without a relation to each other. Therefore, in this report, the abbreviation MME+I is used to distinguish between MME with or without an MMI.

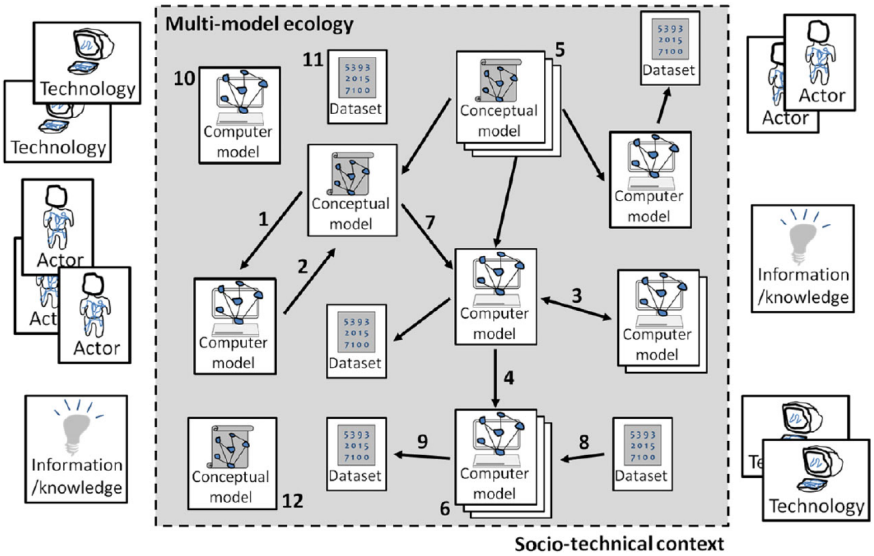

Figure 1.1: Multi-model ecology (Bollinger & Evins, 2015b)

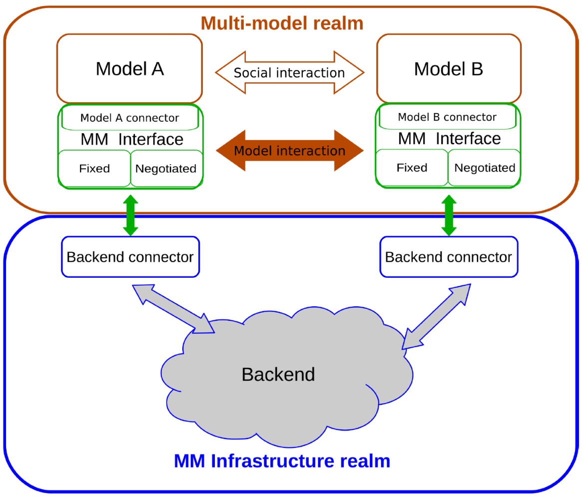

Figure 1.2: Multi-model interaction in (red), interfaces (green) and infrastructure (blue) (Nikolic et al., 2019)

In the current practice of research for Water Resource Management and other research related to the drinking water industry, an MME+I have not materialised. The guiding principle for this research proposal is that if an MMI specifically designed for the integral drinking water system became available, the barriers described by Hare could potentially be overcome due to (1) the new types of resources (MME+I) that become available for water managers and (2) the emergence of new (types of) models and developments in modelling in recent years. In addition, proof of the application of an MME+I could introduce Participatory Modelling as a new technique to engage with actors and stakeholders. Appendix D provides different examples of applications of Participatory Modelling with an MME+I and examples of modelling approaches that could benefit from the existence of an MMI for the drinking water industry that are related -but not limited to the three issues for investment decisions as previously described.

An MME+I has not yet manifested as a research methodology in peer-reviewed research within the drinking water sector. However, this methodology could be very useful for decision-making by coming to a better understanding of the integral water system and its inter-relations (Bollinger & Evins, 2015b; Nikolic et al., 2019).

The main objective of this thesis is to present an exploratory Design Science approach to the design of an MME+I. To explore what is needed to create such a design artefact. At the same time, contributing to scientific progress by delivering a Proof of Concept (PoC) of an MMI for the Dutch drinking water industry. This is done by exploring a new approach for the drinking water industry in the shape of multi-modelling with a Multi-Model Ecology and a Multi-Model Interface (MME+I). The insight gained from designing an MMI and the PoC can then be applied to improve decision-making by making better use of models and the involvement of stakeholders by Participatory Modelling for Dutch drinking water companies.

1.2. Knowledge gap

In preparation for this thesis research project a literature review was performed (See Appendix B). The goal of this literature review was to determine whether or not an MME+I has been applied in drinking water research. The search for literature for the application of an MME+I has not resulted in any documented peer-reviewed attempts at exploring the potential and suitability of MME+I for answering research questions in drinking water research.

From the literature review, it can be concluded there is a knowledge gap in modelling research questions with an MME+I approach for drinking water research.

1.3. Main research question and sub-questions

This thesis argues for an MME+I as a new resource to facilitate PM application for the drinking water industry as presented since there is currently none. The thesis project aims to design and develop an MME+I through two iterative steps.

In order to deliver the proof of concept of applicability for the DWI experiments with a small MME+I will be performed. The assembly of an MMI, data and two models has been applied to research if water demand patterns generated by an ABM-model have an effect in an EPANET hydraulic model.

1.3.1. Main research question

This thesis aims to explore common modelling practices with regard to the types of models, data, algorithms and scenarios that are typically applied for Water Resource Management within Dutch drinking water companies. And apply the knowledge gained in a design process for an MME+I engineered for a Dutch drinking water company by two iterations of the design methodologies. The main research question for the thesis research is:

> How can a multi-model ecology aid the design of a future-proof drinking water distribution system?

1.3.2. Research question 1

The first sub-research question aims to examine further the rationale for including models in an MME. There is currently a lack of experience applying an MME+I for the drinking water industry. What models have been used in an assembly for an MME approach in other fields of science, such as climate change research, energy sector research and research in the transport sector? What was the rationale behind it? This research question is expected to aid in getting a better understanding of the challenges that can arise when designing an MME+I. A literature review will be performed on the design characteristics of existing MMEs.

What are the design characteristics of operational MMEs?

1.3.3. Research sub-question 2

The second sub-research question aims to provide insight into modelling approaches or techniques currently applied at Oasen and its main stakeholders. The aim is to categorise an integral systems overview based on the type of activity within the drinking water chain through semi-structured interviews with colleagues at Oasen. The goal is to gain insight into the modelling formalism, resolution, scale and scope of typically applied models used at Oasen. This is on the assumption that the insights gained from one drinking water company will hopefully be applicable or useful for other drinking water companies.

Which models and modelling methodologies or techniques are currently used at Oasen and relevant stakeholders?

1.3.4. Research sub-question 3

The third sub-research question aims to aid in generating the design for an MME+I. For the design of the MME, a Participatory Design approach will be used, whereas, for the design (logical architecture) of the MMI, a Software Requirement Engineering (SRE) methodology will be used. The logical design will specify the individual components of the MMI and describe how these components interact internally and how the MMI interacts with the MME, outside its system boundaries

What are the design specifications for an MME for the DWI?

1.3.5. Research sub-question 4

The fourth research question aims to document the experience of the design approach and to contribute to the knowledge base as to learn from the design experience in the tradition of Design Science.

What lessons can be learned from an iterative Design Science approach for the design of an MME+I?

The four sub-research questions serve as a structured method, providing insights in order to answer the main research question. A number of design artefacts (deliverables) are required to answer the sub-research questions. These artefacts are described below and are an objective of this thesis research:

4. Literature Review on the design characteristics for an MME
5. An overview of commonly applied models at Oasen and relevant stakeholders from semi-structured interviews
6. Design artefact: MME design by the Participatory Systems Design methodology
7. Design artefact: MMI design by the Participatory Systems Design methodology

8. Design artefact: Multi-modelling strategy for the PoC Use case
9. Modelling and Experimentation of the PoC use case

1.4. Scientific and Societal relevance

This thesis research is a study into a new modelling approach for the drinking water sector by linking existing models. MMES is a perspective on the principle of multi-modelling. MMES bring models and data together in a non-predetermined configuration but can be connected in new configurations at the researcher's discretion. Multi-model ecologies are currently being applied in other research fields such as energy research. A good example of this is the HUES platform, a multi-model ecology for Holistic Urban Energy Simulation. Bollinger and Evins conclude, "Via the combination of modules described in the previous section, we have extracted insights unattainable with any of the modules in isolation" (Bollinger & Evins, 2015a). Bollinger and Evins further indicate that it would be possible to develop a single, comprehensive model of from scratch, it would take significantly more effort than reusing and reconfiguring the existing models in their use case (2015). Other advantages of MMEs are the possibility to approach a problem on a multi-scale, multi-resolution and from a multi-perspective (Mavromatidis et al., 2019).

To date, no MME has been applied in the Dutch drinking water sector. While it is interesting to know whether it is possible to apply a multi-model ecology to discover whether the advantages of the approach in energy research also apply to research in the drinking water sector. Namely, gaining insights that are not possible through applying single-use models. And reducing model development time and effort for comprehensive models by reconfiguring existing models. In addition to the scientific relevance of the first application of an approach that has led to good results in another research field, this research is also of social relevance. Generating an MME+I for the Dutch drinking water sector provides the sector with a tool for improving decision-making with stakeholders. By sharing models, models can be reused, which reduces the development time required for constructing models for the sector as a whole. Furthermore, there is an opportunity for the sector to learn by sharing the implicit and explicit knowledge contained in models and best practices. This is enabled by choosing a Participatory Systems design methodology to generate the design for the MME+I.

1.5. Thesis Scoping

The aim of this thesis research is to design an MME with MMI for Oasen (MME+I), the Dutch drinking water sector and its relevant stakeholders. This thesis uses the **drinking water chain** (see Figure 1.3) as a common thread to shape this geographical and institutional system demarcation.

The institutional scope of this research concerns Dutch legislation and regulations. All stakeholders in scope concern companies with Dutch legal forms and are located in the Netherlands. Since an MME contains, among other things, a distributed IT competency and can therefore, easily be expanded to a different and/or larger institutional scope, this was not chosen in this thesis for the first two design iterations of the MME and MMI design. The rationale for this comes from the idea of starting with a small design and expanding it. instead of trying to start with a design that is too big. The risk is that as a designer you quickly stumble over the complexity.

The drinking water chain was chosen for the functional scope because of the primary process of producing and distributing drinking water to (domestic) customers. All functions related to the primary process of the Dutch drinking water companies can be traced back to the drinking water chain. In practice, drinking water companies can supply water of various qualities to their customers. The starting point in this thesis is drinking water for domestic use. Where there is a deviation from this definition, this will be indicated.

Figure 1.3: Chain of processes for a drinking water company

The last demarcation concerns the topic of multi-modelling itself. This thesis aims to provide a PoC of a multi-modelling use case. Challenges of the multi-model coupling in relation to the Proof of Concept fall within the scope of this thesis. Dealing with these challenges and complexities in depth is beyond the scope of this thesis.

Scope	Definition
Research scope	MME en MMI design, MME and MMI modelling Proof Of Concept
Geographical scope	Netherlands
Institutional scope	Dutch law and legislation
Functional scope	primary function of drinking water production and distribution
Multi-modelling scope	multi-modelling research finding related to Proof of Concept

Table 1.1: Overview of thesis scoping

1.6. Thesis Structure

The context of the challenges for strategic investment decisions and a lack of stakeholder participation, as well as the research approach and objectives, were introduced in this chapter. Chapter 2 will introduce the theoretical background for the thesis research. In the following chapter, chapter 3, the research methodology of this thesis is introduced in detail. In chapters 4 through 9 the thesis research objectives that were introduced in the previous paragraph are presented and described. An overview of the thesis research with the research phases, chapters, methodologies and research questions can be found in Figure 1.4. Chapter 10 introduces the Multi-modelling architecture for an existing energy MME and initiatives from drinking water research that is related to the idea of facilitating an MME+I for the DWI. Discussions and recommendations are presented in Chapter 11. Chapter 12 ends with the conclusions of this research project.

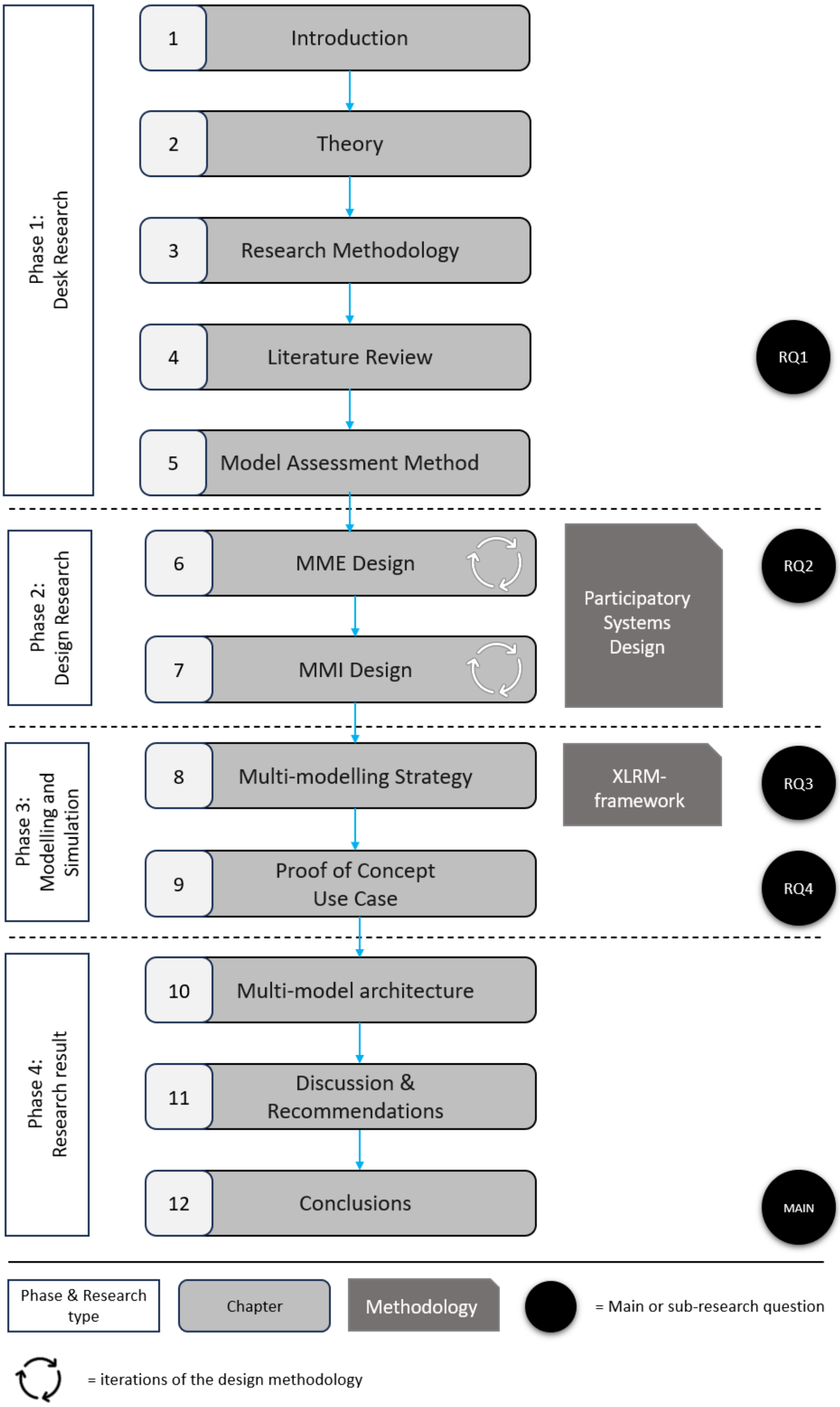

Figure 1.4: Thesis research overview of the research phases, chapters, methodologies and research questions.

2 Theory

The previous chapter provided the context regarding challenges for the Dutch drinking water sector with regard to uncertainties in strategic investment decision-making within individual Dutch drinking water companies. In addition, the external context is related to the possible impact of the effects of climate change. Consequently, arguments have been made for the use of participatory techniques such as participatory modelling to involve stakeholders in decision-making to achieve better decision-making. An MME+I could facilitate stakeholder participation in the drinking water sector, which is the focus of this explorative thesis research. This chapter introduces concepts and theories related the thesis research. Definitions as applied throughout this thesis report can be found in Appendix A: Definitions.

2.1. Design Science

Design Science is ”the scientific study and creation of artefacts as they are developed and used by people with the goal of solving practical problems of general interest” (Johannesson & Perjons, 2021). From this statement, the following can be derived. First, Design Science is a goal-driven process in order to solve problems. The problem is the motive for the process of Design Science. However, the problem does not by definition have to be a real-world problem, a thought experiment defining a problem could also be the driver for a Design Science approach. Second, Design Science is a scientific study, meaning its methodology is rooted in the scientific method (see Figure 2.1). Third, Design Science studies the creation, development and use of artefacts. These artefacts can be studied.

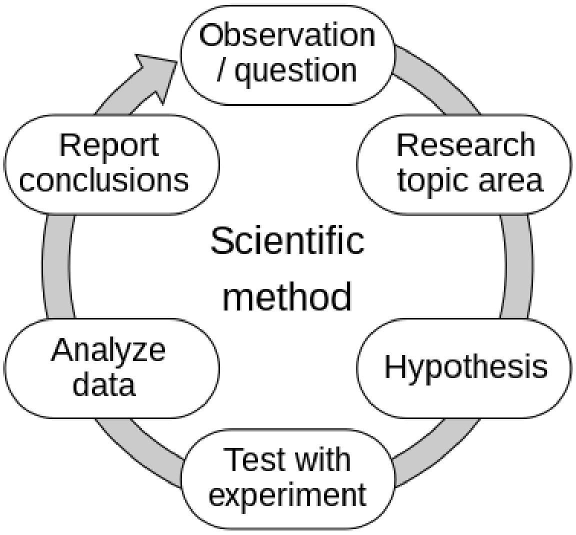

Figure 2.1: Scientific Method (Wikipedia, 2023)

This thesis research is exploratory research into the potential for an MME+I for the drinking water industry. One of the objectives of this research is to generate a design for the MME+I for which the Participatory System Design methodology (PSD) and a Software Requirements Engineering (SRE) methodology will be applied. Both methodologies are applied in order to create a design artefact. A design artefact is a man-made object to address a practical problem (Johannesson & Perjons, 2021). Johannesson distinguishes between four types of design artefacts: (1) constructs, a term, notation, definition or concept (2) Models, where relationships between several constructs are manifested to present a solution to a practical problem (3) Methods, "an expression of prescriptive knowledge by defining guideline and processes for problem-solving" and (4) Instantiations which is a working system that can be used within practice. (Johannesson & Perjons, 2021). In this thesis research, the concept of the MME+I as introduced in Chapter 1 can be considered the construct. Models of the MME and MME (logical architecture) can be found in Chapters 5 and 6. These models are generated by the design methods chosen for this thesis as described in Chapter 3. The final design artefact characterisation will manifest by the Proof of Concept uses case when the multi-modelling strategy is implemented.

Johannesson's definition of the model as "built up from constructs that are related to each other, and represents a possible solution to a practical problem" (Johannesson & Perjons, 2021) is the same as it is applied in the field of simulation research. In practice, a model is often called an *abstraction of the real-world system*. Where the abstraction aids modellers in isolating a point of interest of a system that the modeller would like to investigate. However, the act of modelling does require that the modellers maintain the important characteristics of the constructs and relationships between those constructs in order for the abstraction of the real-world system to be successful.

Design artefacts are communicated through different means which allows for discussion on their appropriateness for the practical problem they aim to solve. When features or structure of design artefacts can be used to make predictive statements they are called design principles (Johannesson & Perjons, 2021).

2.2. Design Patterns

The concept of design patterns comes from the field of Architecture and was introduced in 1977 by Christopher Alexander in his book A Pattern Language (Alexander, 1977). The book is a response to ill-proven practices in contemporary building architecture" and an argument for the reuse of proven solutions (Buschman et al, 2007). These general applicable solutions are called design patterns (Alexander, 1977). The idea of a generic, reusable solution to a common problem spilled over into the field of software engineering (Gamma et al., 2001). And through that field into the field of computer simulation modelling and multi-modelling.

Prior undocumented research into design patterns concluded the following:

- A design pattern is the re-usable form of a solution to a design problem.
- Design patterns are generative from a description in words, graphics or a formalisation.
- Design patterns are aimed at creating or maintaining a certain quality and with the ability to be re-used. Design patterns can be organised hierarchically depending on the field in which they are applied.
- Anti-patterns describe either a design problem that leads to a bad design solution or how to get out of a bad design solution.
- A taxonomy of multi-models has been introduced (Yilmaz & Ören, n.d.) plus design principles (Yilmaz et al., 2007) but no other effort to introduce design patterns could be found in the literature on multi-models.
- Design patterns are also applied as a common terminology or (shared) vocabulary to exchange ideas, opinions and values in a field or in a collaborative manner between layman and experts.

Design patterns can be applied to diverse fields of engineering where a design is needed to meet specific requirements to solve a problem. Consequently, this means engineers apply design patterns to a proposed solution to solve a real-world problem. An example in the context of this research would be the reuse of a part of a logical architecture design of an operational MME+I from another research field.

Design patterns can be applied to the methodology of diverse research fields but are not a methodology by itself. Similarly, a framework can be part of a research methodology.

Design patterns can play an important role in exploring a design space when engineers are looking for a solution for a real-world problem because they contain knowledge about a previous problem and a possible solution. In addition, design patterns are helpful when they have been documented and made available to other designers or engineers.

Design patterns can be useful for multi-model ecologies because they allow proven solutions to be transferred to another field of research. Furthermore, they have the potential to develop into a generic framework for the design of an MME+I.

2.3. Participatory Systems Design

The MME as presented in figure 1.1 consists of a socio-technical context with the actors and technologies that make model development a feasible and valued undertaking, as well as the knowledge, information, techniques, and theory that inform model development (Nikolic et al., 2019). In this perspective the whole of stakeholders and their knowledge interacting with data, models with the hardware and software that facilitate those interactions can be seen as a system of systems. An MME is a participatory system because it can only materialise and continue to exist through the actions and interactions of stakeholders that are a part of the socio-technical context of the system. Because it is a participatory system, the design of an MME requires a participatory system methodology because these approaches are characterised by user-centricity. Designing a participatory system without considering the users' needs, desires, and values would lead to a system design that cannot perform its task. Methodologies for engaging stakeholders in the design process are called Participatory Design methodologies. "Participatory Design (PD) is a collection of design practices for involving the future users of the design as co-designers in the design process" (van der Velden & Mörtberg, 2021). In this thesis applied to design the MME+I.

3 Research Methodology

The previous chapter introduced the theoretical concepts and theories for this thesis. Design Science is the red thread that binds this thesis research. As the previous chapter explained, the four characterisations of design artefacts will manifest throughout this research. This chapter will introduce the overall Research Methodology applied to answer the research questions and achieve the objectives of the thesis research as presented in Chapter 1.

This chapter describes the structured use of research and design methodologies to determine the design of an MME+I and a modelling strategy for the Proof of Concept (PoC) use case. These methodologies are required to answer the main research question and were also introduced in Chapter 1. In this chapter, the four sub-research questions are linked to the applied methodologies required to answer this thesis's main research question.

This thesis research aims to deliver the design of an MME+I and a Proof of Concept (PoC) through a multi-modelling use case. The Participatory Systems Design (PSD) approach was chosen for the MME+I design. The Proof of Concept requires a functioning MMI in computer code and a modelling strategy to answer the research question. The modelling strategy was developed using the XLRM framework and will be presented in Chapter 8. The previous chapter introduced the research objectives required to answer the main and sub-research questions. For this thesis research, the following design deliverables were generated and are presented and discussed in chapters 4- 9 hereafter:

4. Literature Review on the design requirements for an MME
5. An overview of commonly applied models at Oasen and relevant stakeholders from semi-structured interviews
6. Design artefact: MME design by the Participatory Systems Design methodology
7. Design artefact: MMI design by the Participatory Systems Design methodology
8. Design artefact: Multi-modelling strategy for the PoC Use case
9. Modelling and Experimentation of the PoC Use Case

The research approaches and methodologies for the above-stated research objectives of this thesis are presented in this chapter. An overview of the concepts, definitions and terminology as applied throughout this thesis report is provided in Appendix A.

3.1. Literature Review for design requirements solicitation

The first sub-research question aims to find the design characteristics of MMEs that are currently operational or have been applied in other research fields than drinking water research. The methodology applied here is a structured literature review to find the design requirements. The assumption behind the choice of this methodology is that MMEs have certain similar characteristics by definition (see Figure 1-1). By conducting research into applied MMEs, it might be possible to determine the design requirements for an MME beyond those that can be derived from the conceptual model of an MME as introduced in Chapter 1. Furthermore, it might provide insight into the design considerations and alternative solutions of already existing MMEs.

A literature review is considered desk research (secondary research). In their article on how to conduct an effective literature review (Levy & J. Ellis, 2006) make a compelling argument for the merits of a literature review paper to present the body of knowledge of a field. Cooper states there is no formal definition for a literature review, but offers two elements that a LR must contain. First, a literature review presents the work of others and not of the paper's author. Second, "a literature review seeks to describe, summarise, evaluate, clarify, and/or integrate the content of the primary reports." (Cooper, 1988).

3.2. MME design by the Participatory Systems Design

The design methodology applied in this thesis research for an MME design is an adaptation[1] of the methodology taught in several courses of the CoSEM master (SEN1121 Complex Systems Engineering and SEN9115 Participatory Systems) It can be characterized as an iterative, value-centred design approach (van Langen et al., 2023). Within each iteration of the design, the following design phases are addressed:

1. Problem formulation and analysis
2. Mission definition
3. Stakeholder Analysis
4. Requirements Analysis
5. System Synthesis

Table 3-1 presents the diverse set of Design Activities that are to be conducted during each of the Design Phases. The combination of iteratively performing these design activities constitutes the Participatory Systems Design methodology. Parts of the PSD methodology have been applied during this thesis research in order to generate the design of the MME+I.

Design Phase			Design Activity
1	Problem formulation and analysis	challenge	Describe the challenges for the future Participatory System
		context of the challenge	Describe the context in which the challenge is situated
		systems values	Describe the values the Participatory System will embrace
2	Mission Definition	mission statement	Describe the mission of the Participatory System
		mission rationale	Describe how the mission relates to the challenges and including values of the Participatory System
		determination of succes	Describe how to confirm the extent to which your Participatory System is successful in fulfilling its mission (when operational)
3	Stakeholder Analysis	stakeholder identification	Describe the stakeholders who directly and indirectly play a role in the challenge
		stakeholder roles and relationships	Describe the roles and relationships of the stakeholders
		potential conflicts of interest	Identify potential conflicts of interest between stakeholders
		systems scope	Scope the Participatory System by indicating which actors are to be considered in the system and motivate why
4	Requirement Analysis and Specification	stakeholder needs	For each stakeholder in focus, specify the relevant needs in view of the system's mission statement and include the values
		system requirements	For each need, specify and motivate the system requirements (both functional and non-functional) and qualifications (e.g., mandatory, important, desirable)
		system requirements conflict	Identify relations between system requirements and (potential) conflicts between system requirements
		fulfilment criteria	For each system requirement, define fulfilment criteria and a threshold value
		Systems Requirements Structure	Create a Systems Requirements Structure
		Use-case	Create one or more use case diagrams for the lowest-level functional requirements
		Systems Requirements Structure continued	Link non-functional requirements to functional requirements within/between different levels in the Systems Requirements Structure
5	System Synthesis	Alternative analysis and evaluation	Explore the design space with the GMD (Generic Model of Design), alternating between the different components (design process coordination, requirements design, and artefact design), identifying a number of different potential system designs and the requirements they fulfil
		System design analysis	Analyse the alternatives and evaluate their strengths and weaknesses with respect to the requirements and the trade-offs. Indicate the qualitative evaluation criteria.
		System design selection	Best design alternative selection and motivation
		System design analysis	Indicate which requirements have been fulfilled and which not

Table 3.1: Participatory Systems Design methodology

[1]The techniques and methods applied were adapted where necessary so as not to disclose confidential company information.

3.3. Interviews to ascertain model use

The first sub-research question will be answered by having semi-structured interviews with colleagues at Oasen and other relevant stakeholders.

Semi-structured interviews can be a useful technique for gaining a deeper understanding of a research topic. A known limitation is that interviews can be time-consuming due to the required preparation and post-processing of the answers.

In order to create a level-playing field understanding for the interviewees an introduction presentation was given (see Appendix I. In this presentation, the following concepts related to MME+Is were introduced

- Post-normal science
- Complicated versus the complex
- Modelling and computer simulation models
- Top-down versus bottom-up
- Projects versus processes
- Single-use models verse model reuse
- Multi-Model Ecology's
- Multi-Model Interface
- Participatory Systems
- Participatory Modelling.

These interviews resulted in an overview of models that employees of Oasen and relevant stakeholders often apply. In order to create this overview, a method was developed to assess the meta-data on the models. The method and an overview of models are presented in Chapter 5.

3.4. Multi-modelling strategy for the PoC Use case

The PoC for the MME+I will be delivered via a multi-modelling use case in Chapter 8. The XLRM framework is the methodology applied to combine the Agent-based Model and the EPANET hydraulic model. Both models and their simulation software will be presented in Chapter 8. In this paragraph, the XLRM framework will be presented.

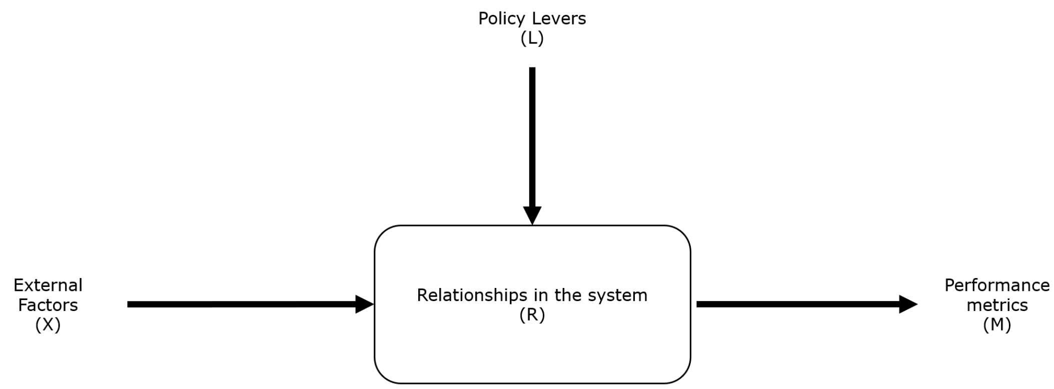

Figure 3.1: XLRM-framework (Lempert et al., 2003)

The XLRM framework (see Figure 3.3) was introduced in 2013 by Lempert et al., as a new tool to aid decision-makers in robust decision-making (Lempert et al., 2003). The framework is useful to aid policymakers with long-term policy analysis. It is applied "to craft potentially implementable policy options that consider the values and beliefs of various stakeholders" (Lempert et al., 2003).

The first element is the external factors (“X”). These are mainly uncertainties that affect the system but are outside the control of policymakers. The policy levers (“L”) are the interventions at the disposal of policymakers. The relationships in the system (“R”) refer to model structure and features. The performance metrics (“M”) are outcome variables to be observed (Jafino et al., 2021).

The XLRM framework is a commonly used framework for structuring information in model-based decision support (Kwakkel, 2017; Lempert et al., 2003).

By using the system demarcation of the XLRM framework a general research question can be morphed into the following statement:

What is the effect of *policy levers* on the *output variables* under the conditions *of the system and its internal relationship*s given *external factors*?

The XLRM framework will be applied to the main research question in order to determine the PoC use case multi-modelling strategy in Chapter 9.

4

Literature Review

The previous chapter introduced the research methodology applied in this thesis research in order to answer the main and four sub-research questions. Answers to the sub-research questions will aid in answering the main research question and the four sub-research questions, each with its own approach. The methodology to answer the second sub-research question ("What are the design characteristics of operational MMEs?") is a literature review, which will be presented in this chapter.

4.1. Introduction

In order to gain an in-depth understanding of the current knowledge regarding approaches to multi-modelling and the application of MMEs in the real world, a literature review was conducted. A literature review is a proven method to gain state-of-the-art knowledge on a topic (Wee & Banister, 2016). The main goal of this review is to determine the design characteristics of operational multi-modelling approaches or MMEs in other fields of research in order to build upon extant knowledge and allow for the cross-pollination of ideas and practices between scientific research fields. Furthermore, this literature review was conducted in order to answer sub-research question 2. This chapter defines and discusses the key concepts, definitions and design requirements for multi-modelling and MMEs. As well as the challenges and impediments that were identified from the reviewed literature.

4.2. Literature selection method

There are various approaches on how to conduct a search for relevant literature. Typically, keywords and logical expressions are applied to one or multiple online search engines for peer-reviewed literature. That approach proved inadequate in this case due to the overwhelming amount of ill-suited articles that were returned for search strings combining "Multi-Model Ecologies AND Design Characteristics" or variations on those search terms. Instead, another approach was adopted to come to a body of relevant literature for the review.

In order to find relevant literature on the design principles and characteristics of MMEs the following search for literature was conducted. Three articles that are listed below were selected from the body of literature found in prior research (see Appendix B and C).

1. Multimodel Ecologies, Cultivating Model Ecosystems in Industrial Ecology (Bollinger et al., 2015)
2. Multi-model ecologies for shaping future energy systems: Design patterns and development paths (Bollinger et al., 2018)
3. A data model to manage data for water resources systems modelling (Abdallah & Rosenberg, 2019)

The first article was selected because it is the origin of the idea of "cultivation of an evolving set of resources that with some additional effort can be recombined and reconfigured for different purposes" (Bollinger & Evins, 2015b). The pre-assumption here is that if a second article cites the first article there is a good chance that concepts and definitions are applied adequately similarly. The second article was chosen because it is consistent in concepts and definitions with the first article so the same pre-assumption applies. Additionally, the article states the lack of knowledge on MME initiatives from a design and management perspective (Bollinger et al., 2018). The third article was selected because of its development of a general approach for modellers in Water Resources Management " that only requires doing the work once but allows others to re-use their effort in their other endeavours" (Abdallah & Rosenberg, 2019). Which can be characterised as a bottom-up approach to a participatory system that could evolve into an MME. Additionally, the focus of the third article lies more on data. In contrast, the first two articles opt for a "coupling of models" perspective. Since data and models are an intrinsic part of any MME combining these perspectives should be beneficial for the design of the MME+I.

The articles that have cited the three initially selected articles were found via Google Scholar. All articles were scanned via title, keywords and abstract to determine their relevance and select the article for the body of literature for this review. Interesting citations in the articles have been further explored and, in some cases, added to the body of literature. An overview of the reviewed literature can be found in Appendix H.

4.3. Concepts and Terminology on multi-modelling

The literature review from prior research made the ambiguity insightful on definitions. The same is true for the reviewed literature presented in this chapter. This paragraph aims to present the concepts and definitions in a consistent and precise fashion. The images (Figure 4.1 - 4.3) in this section each present two concepts in juxtaposition to provide insight into the concepts and definitions and their relationship to each other. Throughout the articles, terms such as coupled modelling, coupled component modelling, multi-modelling and Integrated Assessment Modelling are typically used when the reviewed research applied two or more models and either a workflow to manage the data or applied a coupling of some sort. This coupling can be a direct or indirect data flow between the models or a social process where researchers from different fields work on integrating their conceptual models and knowledge into an operational model and a computer simulation model.

Figure 4.1: Single use models vs. multi-modelling terminology

Voinov and Shugart define integrated modelling as "the method that is developing to bring together diverse types information, theories and data originating from scientific areas that are different not just because they study different objects and systems, but because they are doing that in very different ways, using different languages, assumptions, scales and techniques" (Voinov & Shugart, 2013). Here the notion of the method which can include modelling, is more than the act of making a model but it encompasses different paradigms from different scientific fields of research. They differentiate between integral models and the assembly of existing models (integrated models).

Figure 4.2: Integral models vs. integrated models

"Integral models are generally constructed by a single modelling team that translates data and information from various fields into a single formalism. Such models are often built from scratch, and their components cannot be easily separated or reused" (Mavromatidis et al., 2019). In contrast, integrated models are "generally assembled from existing components that can work either in combination or independently" (Mavromatidis et al., 2019).

Figure 4.3: Single use models vs. systems of models

The idea of integrated models, systems of models or multi-models introduces the concept of how these models are linked or coupled. This can be a tight coupling or a soft-link coupling (Brandmeyer & Karimi, 2000). However, an integral modelling approach from IAM can be considered a tightly coupled model, where the coupling occurs in the model itself. The model coupling then takes place before the construction of the model in the model conceptualisation phase where the system is demarcated and important concepts are abstracted and inter-related.

This is the opposite of coupling two or more (existing) models with an approach that is known as Coupled Component Modelling (CCM) (Belem & Saqalli, 2017) where model coupling takes place after the models have been conceptualised and constructed. Which can be considered to be an approach to achieving IAM. See Figure 4.4, where the arrow goes from Coupled Component Modelling towards IAM to denote a way to achieve IAM.

Figure 4.4: Coupled Component Modelling to achieve Integrated Assessment Modelling

Kelly et al. state "that Coupled Modelling or Coupled Component modelling is a relevant modelling approach to achieve IAM" (Kelly et al., 2013) in (Belem en Saqalli, 2017)). However, "Bollinger et al. offer a complementary perspective, suggesting that effectively capturing cross-scale and cross-domain interactions requires the development of not just single models, but the systematic cultivation of interacting systems of models, a.k.a. multi-model ecologies" (Mavromatidis et al., 2019).

The important issue to note here is that "a multi-model ecology is not an approach, but rather a perspective—a way of conceptualizing systems of interacting models that emphasizes their evolutionary and sociotechnical embedded nature" (Bollinger & Evins, 2015b). The key idea presented here is that due to the fact that the models are part of a socio-technological context which is dynamic and evolutionary in nature, so are the models. This makes it conceptually easier to differentiate between multi-model ecologies and "ecosystems of applications, models as digital twins or systems of models (Manfren, Nastasi, Groppi, et al., 2020) or software ecosystem coupling (Abdallah et al., 2022) where this concept is not presented as such in the reviewed literature.

4.4. Rationale for a multi-modelling approach

The previous paragraph presented the concepts and terminology from the reviewed literature. In this paragraph, the rationale for adopting a multi-model methodology is presented. Three rationales were found, and these are presented with a catchphrase to introduce the topic and an explanation from the literature.

The whole is more than the sum of its parts
The first rationale for multi-modelling can be characterised by the synergy that emerges when distinct stand-alone resources such as data and models are combined in new configurations. Bollinger and Evins state that "the combination of computational modules (a collection of input data and at least one model) employed allows us to extract insights unattainable with any of the modules in isolation"

(Bollinger & Evins, 2015a; Evins, 2017). In his paper on the Holistic Urban Energy Simulation (HUES) platform -an extendable simulation environment for the study of urban multi-energy systems- Evins argues in favour of a holistic approach to modelling (and optimisation) in order to "better capture the interactions that characterise problems in the urban energy realm" (Evins, 2017)).

The ability to capture multiple dimensions of a research domain
The second rationale for multi-modelling comes forth from the ability to capture multiple dimensions of a research domain. By introducing new configurations of data and models, it is possible to "cover the multiple, interconnected and interacting aspects of the domain" (Mavromatidis et al., 2019). Mavromatidis et al, further argue that there is an absolute need for such a perspective because "decision-making becomes more difficult due to interconnectedness (of systems) and the need to consider multiple economic, environmental, social and energy policy aspects (Mavromatidis et al., 2019). Something that is supported by Bollinger and Evins (Bollinger & Evins, 2015b).

Multi-modelling is more efficient due to reconfiguration and re-use
The third rationale found in the reviewed literature for multi-modelling is that it is more efficient to reuse and reconfigure existing datasets and models. Bollinger and Evins state that "facilitating the sharing, identification and reuse of models reduces the effort necessary to address research questions" (Bollinger & Evins, 2015a). They further state that it would be possible to construct a single, comprehensive model but that would require a significantly greater effort (Bollinger & Evins, 2015a). Abdallah et al, gives insight into the 5 issues (see Table 4-1) modellers in dealing with decision-makers and stakeholders. They argue in favour of an approach allowing the work to be only done once and re-used (Abdallah et al., 2022; Abdallah & Rosenberg, 2019).

No.	Description of characteristic	Source
1	Systems modellers must manage and store input and output data and track metadata	Not specified
2	Systems modellers need to set up socio-economic and infrastructure management scenarios and track differences in input and output data	(Abdallah & Rosenberg, 2019)
3	Systems modellers need to visualize water system components and their connectivity as nodes and links	Not specified
4	Systems modellers must plot input and output data to communicate model results and engage stakeholders with minimum technical difficulties	(Brown et al., 2015)
5	Systems modellers are increasingly required by funding agencies and journals to publish the final modelling data, code, and results to support reproducible science	(D. E. Rosenberg & Watkins, 2018; D. Rosenberg et al., 2021; Stagge et al., 2019)

Table 4.1: Challenges for system modellers (Abdallah et al., 2022)

Cross-contamination of ideas and approaches between research fields
The fourth rationale for multi-modelling comes from the possibility of combining models and knowledge from different research fields. When data and models become available for reuse and reconfiguration the knowledge from the research field the model originates from also spills over as part of the (implicit) knowledge of a research field is embedded in the model (Johannesson & Perjons, 2021) Through a multi-model approach, it is possible to achieve knowledge integration from different disciplines where all types of applications are theoretically possible (Kelly et al, 2013) in (Belem & Saqalli, 2017).

4.5. Design characteristics from the reviewed literature

In this paragraph the design characteristics for operational MMEs, as found in the reviewed literature are presented and discussed. The design characteristics found in the literature were found without any further explanation. Those articles (source) that presented a conceptual model, logical architecture or description of a multi-modelling approach presented the end-result of a prior design exercise. Consequently, there is no description in the reviewed literature about the rationale for some of the design characteristics nor can alternatives or an alternatives selection to these characteristics be found. This means that the literature review has help to gain insight into the what of design characteristics but not the how.

Design Characteristic 1
Cultivation of an evolving set of resources that with some additional effort can be recombined and reconfigured for different purposes (Bollinger & Evins, 2015a)
The rationale for this design characteristic comes from the idea the MME is dynamic and evolves over time. Specifically, this means that the resources of the MME should have a “location” where they are kept such as a model repository, data repository as well as the meta-information for both. In addition certain software or software libraries should also be “kept” as certain versions of models are specifically designed for a specific software version.

Design Characteristic 2
Possibilities for model integration are not predefined, but emerge over time from ongoing development efforts (Bollinger & Evins, 2015b).
This design characteristic ensures that the MME has flexibility as to prevent locked-in situations where design choices in the present narrow the decision space for the future (source). Furthermore, it enables the relevance of the MME to the future due to the ability to adapt. In addition to that it alleviates the current design task for an MME because it supports the need to design a future-proof system without the need to predict the future.

Design Characteristic 3
An extendable simulation environment (Bollinger & Evins, 2015a)
This characteristic relates to the idea of an MME as a dynamic and evolutionary system where new resources can be added to the repositories in order to keep the system relevant and innovative for future research endeavours.

Design Characteristic 4
(Open source) data and models (Abdallah et al., 2022)
A number of articles (sources) made an appeal or referred to an appeal for the application of open data in energy systems modelling (article Stefan). The MME for Oasen should support the use of open data sources.

Design Characteristic 5
A repository with modules of code and data (Evins, 2017)
The HUES platform (Bollinger & Evins, 2015a; Evins, 2017) implemented a model repository and a programming code repository next to a data portal. In their architecture data and models are combined in so-called modules. These modules presumable contain a model and its relevant input data. Other interesting sources of data can then be made available through a data portal or a data repository.

Design Characteristic 6
Collections of modules (Evins, 2017)
The collection of modules refers to the above-mentioned combination of input data and model.

Design Characteristic 7
Facilitate the linkage of models (Bollinger & Evins, 2015a; Pauliuk et al., 2017)
The MME models become part of a workflow where model inputs, models and outputs are linked to a defined workflow run. Subsequently, this requires meta-information on input and output data and the models in the MME.

Design Characteristic 8
Module repository to enable sharing of modules across different platform users (Bollinger & Evins, 2015b)
This design characteristic refers to the accessibility of an MME for users from different platforms. For Operating Systems, this could refer to Apple, Linux and Windows users.

Design Characteristic 9
A semantic wiki that details the functionality and inter-connectivity of modules (Abdallah et al., 2022; Bollinger & Evins, 2015a; Evins, 2017)
Both stakeholders as the MMI have to have knowledge about the resources of the MME. This requires a semantic wiki that is human and machine-readable. In addition, it requires that metadata on the resources is available. Without the metadata model coupling is not possible in the MME.

Design Characteristic 10
A script to pass information and execution commands (Evins, 2017)
This design characteristic is the only referral found in the reviewed literature to the implementation of an MMI and is not mentioned as such. A script can be considered as an early stage of development for an MMI whereas a mature MMI would allow for an automated workflow.

Design Characteristic 11
Publish systems modelling data with contextual metadata to enable data discovery and analysis (Abdallah et al., 2022; Manfren, Nastasi, Tronchin, et al., 2021)
Documenting metadata on the model run does not only allow for data discovery and analysis. In addition, it facilitates learning by the stakeholders as it enables them to gain insights from model runs and the outcomes performed by other stakeholders.

Design Characteristic 12
A version control system to facilitate synchronisation of code between the module repository and the files on the computers of individual developers (Bollinger & Evins, 2015a). Models require a software environment to execute the model its algorithms. These software environments can be stand-alone or have software dependencies on their own. As software is developed to add new functions or to improve the software by fixing bugs or weaknesses that potentially could be exploited new versions are introduced. These new versions introduce a risk of inoperability by incompatible software versions. In order to prevent this software versions have to be added to the repository and version control is essential. In addition, metadata on modelling software and the required libraries or packages has to be made available.

Design Characteristic 13
Controlled vocabularies to relate terms across data sets and models (Abdallah et al., 2022). Metadata on the naming conventions applied for the resources has to be made available to ensure operability.

Design Characteristic 14
Visualize, edit, and compare networks, data sets, and scenarios in an online application (Abdallah et al., 2022; Evins, 2017). A Graphical User Interface (GUI) to visualise the resources of the MME and opportunities for resource coupling can create opportunities for engagement with the MME modelling environment.

4.6. Logical Architecture Design

Of the reviewed literature, two articles presented their logical architecture for an MME. The HUES platform as depicted in Figure 4-5 (Bollinger & Evins, 2015a). And the Software Ecosystem for Water Resource Management (see Figure 4-6) (Abdallah et al., 2022).

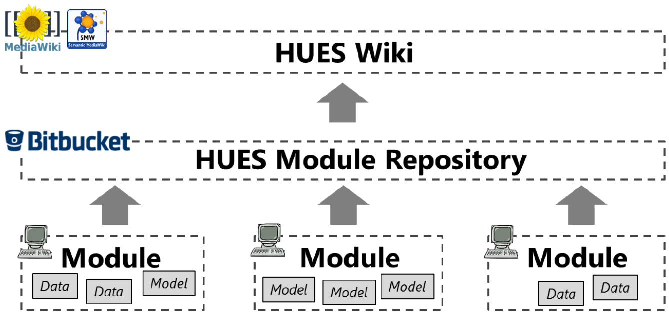

Figure 4.5: The three-layered architecture of the HUES platform (Bollinger & Evins, 2015a)

The HUES platform is an open source system. In the overview of the architecture, this can be deduced from the dotted line around the components of the architecture. The architecture consists of 3 layers within which information is exchanged from the bottom layer with the modules consisting of clustered models and data sets or clustered data sets. The HUES Module Repository is hosted on Bitbucket, a Git-based source code repository hosting service. Furthermore, the HUES wiki also uses existing internet services. What is striking is that no user is shown in the image. In addition, there is a lack of a clear interface to call the modules for a model run. Finally, the features of the HUES Module Repository are not shown in this overview.

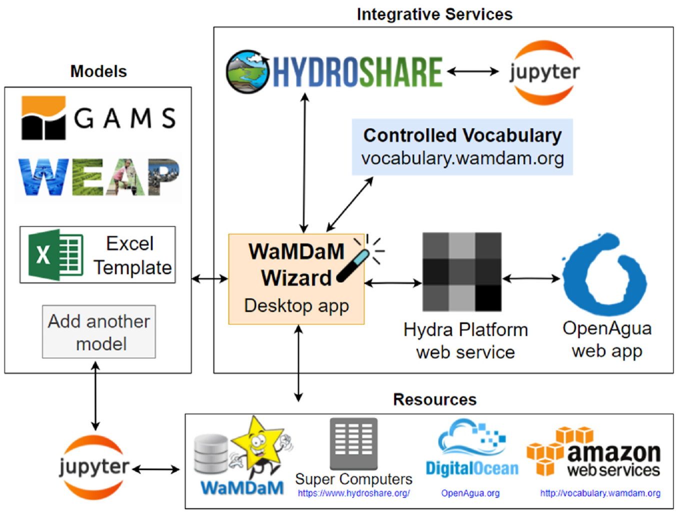

Figure 4.6: Software ecosystem architecture (Abdallah et al., 2022)

In the software ecosystem architecture of Abdallah et al (Figure 4.6), the user is also not presented. However, here the user interface is clearly defined as a desktop application (WaMDaM Wizard). On the right side an overview of the various applications in which models can run, is presented . But here, there is a link between the models and the datasets that are better defined in the example of the HUES platform. Furthermore, the architecture provides an overview of the resources responsible for hosting the necessary software to run the models. This name differs from the definitions within this thesis, where the resources are defined as the components of the MME Modeling Environment (software, models and data). What is also striking is the application of Jupyter Notebook in the connection between the resources and the Models and as an application related to Hydroshare. The functionality of an MMI, as defined in this thesis, does not occur within one entity but is distributed across multiple entities in the software ecosystem. The controlled vocabulary is a feature designed to handle the different naming conventions as applied in the models that form the software ecosystem.

This chapter presented the findings from the literature review for operational MMEs design characteristics. The conclusions from this review are presented in Chapter 11, Conclusions and Recommendations. In the next chapter, a Model Assessment method will be presented to aid in acquiring meta-data from models that are applied at Oasen.

5

Model Assessment Method

The previous chapter presented the design characteristics derived from operational MME+Is. In this chapter, a method to access the meta-data for models is presented. The goal of the first sub-research question (Which models and modelling methodologies or techniques are currently used at Oasen?) is to achieve insight into the modelling formalism, resolution, scale, and scope typically applied models used at Oasen. The rationale for it is to document the meta-data on models that are applied within the drinking water sector so these models can be made available in the MME+I for use and reuse. To support this use and reuse, meta-data on the models have to be made available in order for participants to learn about the resources of the MME+I. This thesis introduces a structured approach to acquiring relevant meta-data information through a Model Assessment method as described in Table 5.1.

Meta-data category	Definition
Organisation	Name of the organisation who owns the model
Model name	Name of the model
Model description	Brief description of the purpose of the model
Type of model	Categorisation to express the general application
Modelling formalism	Modelling framework containing the basic assumptions, ways of thinking, and methodology
Resolution of Attributes	Level of detail of models' attributes
Resolution of Behaviour	Level of detail of the models' behaviour
Resolution of Entities	Level of detail of the models' entities
Resolution of Processes	Level of detail of the models' processes
Spatial resolution	Level of detail of the model's space
Temporal resolution	Level of detail of the model's handling of time
Scale: Temporal	Describes the temporal scale of the model
Scale: Spatial	Describes the spatial scale of the model
Software env.: platform	Hosting/software for the model
Software env.: operating system	Operating system for the software of the model
Software env.: engine	Additional software required to run the model
Open source software?	True or False
License & Type	If a licence is required to use the model
Model accessible through an API?	True or False
Model inputs	List of model inputs and units
Model outputs	List of model outputs and units

Table 5.1: Model meta assessment method

Based on semi-structured interviews with Oasen colleagues, an inventory of the models used within Oasen was made. An overview of the 10 most important models is included in Appendix G). Two examples of the result of the application of the Model Assessment Method can be found in Tables 5.2 and 5.3.

Meta-data category	Definition
Organisation	KWR Water Research
Model name	Well Field Scheduling Optimiser (WFSO)
Model description	To model the effect of a change in the sourcing on the quality of the drinking water in the clean water celler
Type of model	Hydrology modelling
Modelling formalism	Mathematical optimisation
Resolution of Attributes	abstracted 1-level aquifer
Resolution of Behaviour	N.A.
Resolution of Entities	N.A.
Resolution of Processes	N.A.
Spatial resolution	real-world (x,y,z)-coordinates
Temporal resolution	real-world time
Scale: Temporal	real-world representation per 16 hours
Scale: Spatial	real-world representation
Software env.: platform	N.A.
Software env.: operating system	Windows
Software env.: engine	Python
Open source software?	False
License & Type	Indicates if licence is required to use the model
Model accessible through an API?	False
Model inputs	Physical characteristics of a well and water quality
Model outputs	circuit diagram and expected water quality

Table 5.2: Model meta assessment method applied for Sourcing

Meta-data category	Definition
Organisation	Bentley
Model name	OpenFlows WaterGEMS
Model description	Decision-support tool for water distribution networks
Type of model	Hydraulic model
Modelling formalism	Numerical modelling
Resolution of Attributes	Distribution network assets
Resolution of Behaviour	N.A.
Resolution of Entities	N.A.
Resolution of Processes	N.A.
Spatial resolution	real-world (x,y)-coordinates
Temporal resolution	defaults to 15 minutes
Scale: Temporal	real-world representation
Scale: Spatial	real-world representation
Software env.: platform	N.A.
Software env.: operating system	Windows 10 Pro, 64-bit
Software env.: engine	Engine is EPANET which is integrated in the software
Open source software?	False
License & Types	Commercial
Model accessible through an API?	False
Model inputs	distribution network and water consumption per connection
Model outputs	Water supply, pressure and flow per node or pipe

Table 5.3: Model meta assessment method applied for Distribution

The Model Assessment Method provides insight into the possibilities for loose model coupling by providing an overview of the model's resolution, scale and outputs. In addition, it provides insight into the software requirements necessary to maintain the model's functioning.

This chapter presented a method to assess the meta-date of models as part of the desk research phase of this thesis research. In the following chapters, the focus will shift towards the design of the MME+I and the required artefacts for the Oasen Multi-Model Ecology. For that purpose, the design characteristics in this chapter will aid in determining the design requirements for the MME+I in the following chapters.

6
Design Artefact: MME Design

The previous chapter presented the Model Assessment methode for aquiring model meta-data. This chapter presents the results of the Participatory Systems Design methodology followed to design the MME as discussed in Chapter 2 Research Methodology. The design of the MMI is done using a Software Requirements Engineering approach and is discussed in the following chapter. This chapter goes through the phases of the Participatory Systems Design methodology and presents the results per phase.

6.1. Problem formulation and analysis

In this phase of the PSD methodology, the challenges and the context for the challenge of the future Participatory System are mapped out and discussed. In addition, the values that drive the systems design are introduced. The challenges for the drinking water sector regarding strategic investment decisions and deep uncertainty on the possible effects of climate change, and a lack of participatory techniques to engage with stakeholders were introduced in Chapter 1.
The challenges for the drinking water sector in the Netherlands lies in the fact that numerous investment decisions have to be made that will impact the future performance of the drinking water system. First, the current extraction and production capacity must be expanded to meet future drinking water demand based (IcaStat, 2018).

Second, there is a great demand for end-of-life replacement of pipes in the drinking water infrastructure (DWI). these infrastructures were often built after WWII and are reaching the end of their lifespan. they have to be replaced before they leak or break and cause outages. This end-of-life replacement task requires significant investments (Selvakumar & Tafuri, 2012).

Third, an investment challenge of a lesser financial magnitude but with an expected great impact on business operations is related to gaining operational control over the drinking water distribution network by integrating state-of-the-art sensor technology. And developing reporting or visualisation software tools such as dashboards or Digital Twins to relay the operational status of the network to its operators. The working principle of drinking water distribution systems hasn't changed since their first application in the 19th century. Still, their complexity has increased due to growing customer connections and changing demand patterns. Traditional water distribution systems operate as a black box, whereas contemporary distribution systems equipped with sensor technology offer (near) real-time insights for business operations.

Operational budgets have recently come under pressure due to a decline in water sales caused by higher energy prices due to the war in Ukraine. In addition, there is deep uncertainty regarding the effects of climate change on day-to-day operations (sourcing and production) and deterioration of assets in the subsurface.

Finally, there is a lack of participation in the sector to facilitate stakeholder engagement. The mission of the MME+I is related to the United Nations Sustainable Development Goal number 6, 'ensuring availability and sustainable management of water and sanitation for all" (UN, 2023). The values and their description for the MME are presented in Table 6.1.

Values	Description of the values
Accessible	A participatory system where the participants have access to all of the resources of the MME.
Empowerment	A participatory system that enables its different types of users to perform according to their designated role in the system.
Enduring	A participatory system that maintains its function over time regardless of the entry or exit of participants.
Engagement	A participatory system that facilitates its users to interface with the system, its resources and other participants.
Evolutionary	A participatory system that fosters an increase in resources and interactions between the resources.
Learning	A participatory system that contains meta-information on the participatory systems' components, resources and itself to support the transfer of knowledge.
Replicable	A participatory system with methods and procedures that produce the same results from model runs with the exact same parameterization and model run settings on each model run.
Scalable	A participatory system that facilitates the entry of new participants and resources.
Secure	A participatory system that is only accessible to its participants.
Traceable	A participatory system that keeps a record of the actions performed with its resources that are accessible to all other participants.
Trust	A participatory system that is safe, secure and provides opportunities to learn about the system and its components.

Table 6.1: Values and their their description

6.2. Mission Definition

In this phase of the PSD methodology, the mission of the MME is formulated based on the previously introduced values.

The mission of an MME for Oasen is to facilitate *enduring* and *evolutionary* data and model use and reuse, support *replicable* decision-making processes and improve *learning* throughout the Dutch drinking water chain.

The values of the system need to be related to its mission to enable the system to succeed in fulfilling its mission (see Table 6.2). Table 6.3. shows the values and the manner to measure the success of the system.

Values	Relationship between the values and the mission
Accessible	Participants should be able to access the system in order to engage with its resources and engage with other participants. If the system is (partly) inaccessible, it may lose its appeal to its users.
Empowerment	For the mission to succeed users of the system must feel empowered in order to play their role in the system. A participatory system without users engaging with it is useless.
Enduring	Participants' perceptions and interests may change over time, and they should be free to withdraw as active participants. However, their withdrawal should not change the functionality of the participatory system at that time.
Engagement	Without the engagement of participants, the MME will not be dynamic or evolutionary. It would not support emergence, and there would be no added value derived from the participatory system for the users of the system.
Evolutionary	Adding new resources will aid in opportunities for continued utilisation of the system by its users and the emergence of new resources and possibilities for interaction of resources and participants.
Learning	the participatory system should be well-documented for participants to be well-knowledgeable quickly in order to recombine or reconfigure the systems' resources.
Replicable	the participatory system should support the replicability of the model runs in order for it to be a reliable system to facilitate better decision-making processes in the drinking water industry.
Scalable	new participants should be able to enter the system to support the enduring and evolutionary development of the participatory system.
Secure	the system should be secure in order to enable sharing of resources by the participants.
Traceable	This value is aimed at building trust between the parties involved by giving participants full disclosure. Secondly, it can aid in sharing knowledge within the participatory system by knowledge sharing.
Trust	A lack of trust in the system might prevent users from interacting with the system of the sharing of resources.

Table 6.2: Relationship between the mission of the system and its values

Values	Measurables of values
Accessible	System availability: number of user login per time period
Empowerment	System survey: periodic survey to determine if the user feels that the functionality of the system align with its role in the system.
Enduring	System records: periodic report on the meta-data of the system.
Engagement	System usage: statistics report on meta-data of the system
Evolutionary	System development: number of users, data sources, models and software per annum
Learning	System usage: number of rationale published for model runs and entries in teh semantic wiki
Replicable	Systems reliability: monthly check on replicability by testing and comparing model runs with the same parameterisations.
Secure	
Scalable	System scalability: number of user accounts created.
Traceable	System records: number of documented model runs and number of model runs for which user specified the rationale.
Trust	System survey: periodic survey to determine users' trust in the system and the manner in which the user feels involved with the system

Table 6.3: Measure of the success of the system

6.3. Stakeholder Analysis

During this phase, the direct and indirect stakeholders are identified. For this thesis, this was done by taking the simplified drinking water chain and identifying the activities that take place for each function to determine the relevant stakeholders. Stakeholders are categorised as direct stakeholders when they can provide the MME+I with either data or models and potentially have an interest in participating in an MME+I for Oasen. Indirect stakeholders are stakeholders who are potentially influenced by Oasen using an MME+I but who do not participate in any Participatory Modelling effort. Table H.1 in Appendix H provides an overview and a description of the relevant direct and indirect stakeholders. Table H.2 in Appendix H presents an overview of the stakeholders and their interests and roles in the system.

After determining the relevant stakeholders for the Oasen MME+I it is important to identify the stakeholders that are selected to play a role in the initialisation of the participatory system and the rationale, these can be found in Table 6-4.

Stakeholders in scope	Rationale
Dutch drinking water companies	Oasen and the Dutch drinking water companies collaborate on their research efforts in the Industry Survey (BTO). This is research done by KWR. This research generates many models which could be a part to the MME+I.
KWR	KWR is a research institution of which the Dutch and a Belgian drinking water company are the stakeholders. the basis of research at KWR is the Industry Survey (BTO) of the Dutch drinking water companies.
Oasen	the initiative for the MME+I for the Dutch drinking water sector originated at Oasen
TU Delft	TU Delft is involved through the supervision of this thesis research and an agent-based model from prior research is used for the PoC multi-modelling use case.

Table 6.4: MME stakeholders in scope

Now that the initial stakeholders of the MME+I are identified, the next step is to determine which of the values of the participatory system are of importance to the different stakeholders in order to help determine the requirements of the system. This can be found in Figure 6.2 Stakeholder Roles and Values.

6.4. Requirement Analysis and Specification

The previous paragraph identified the initial stakeholders of MME+I. In this paragraph, the values of the participatory system and the needs and desires of the stakeholders are related in order to generate the system's requirements and with those, the Systems Requirements Structure. As different departments within the companies of different stakeholders may perform different roles in order to contribute to the overall goals of the companies, different types of roles are introduced here for each of the stakeholders in scope as is presented in Table 6.7.

Stakeholders	Roles	Accessible	Empowerment	Enduring	Engagement	Evolutionary	Learning	Replicable	Scalable	Secure	Traceable	Trust
Oasen Management Team	decision maker					x		x	x			x
Oasen Assetmanagement Team	user	x	x	x	x		x	x			x	x
Oasen Environment and stakeholder management	user	x	x	x	x		x	x			x	x
Oasen Technology Team	user	x	x	x	x		x	x			x	x
Oasen Team Water distribution	user	x	x	x	x		x	x			x	x
Oasen IT Management	lower tier decision maker					x		x	x	x		x
Oasen IT	application manager	x							x	x		
Drinking water companies Management Team	decision maker					x		x	x			x
Drinking water companies employees	user	x	x	x	x		x	x			x	x
KWR Management Team	decision maker											
KWR researchers	user	x	x	x	x		x	x			x	x
TU Delft	user	x	x	x	x		x	x			x	x
TU Delft	designer	x	x	x	x	x	x	x	x	x	x	x

Figure 6.1: Stakeholder Roles and Values

Stakeholder department	Role
Oasen Management Team	decision maker
Oasen Environment and stakeholder management	user
Oasen Team Asset management & Technology	user
Oasen Team Water distribution	user
Oasen IT Management	lower tier decision maker
Oasen IT	application manager
Drinking water companies Management Team	decision maker
Drinking water companies employees	user
KWR Management Team	decision maker
KWR researchers	user
TU Delft University	user
TU Delft University	system designer

Table 6.5: Initial stakeholders and roles in the MME+I

The various roles in the table above are indicative and may actually be assigned to one or more people in an organisation. The roles of Oasen IT Management, lower tier decision maker, Oasen IT, and the application manager can also occur with the other stakeholders within the MME+I for Oasen. Also, from the point of simplicity, it was decided to mention this once. Tables 6.6 - 6.9 specify the needs and desires based on the values of the decision-makers, users, IT managers, and application managers' roles.

Value	Needs and Desires
Evolutionary	Decision-makers require the entry of new resources in order for the system to be of interest for the users and offer possibilities for cross-pollination and learning.
Replicable	decision-makers require valid and verifiable results from research by users to support the decision-making process.

Value	Needs and Desires
Scalable	decision-makers require the entry of new participants and resources to grow the system in order to create new opportunities and innovations in research by users (network effect)
Trust	decision-makers require a system that is safe, secure and provides opportunities to learn so that users are willing to interact with is

Table 6.6: Decision-makers values, needs and desires

Value	Needs and Desires
Accessible	users require access to all the resources in order for them not to be hindered in their research
Empowerment	users require interaction with the resources AND users can benefit from positive interactions with other participants
Enduring	users require a stable participatory system that does not lose a part of its functions during research
Engagement	users require that the system has an interface to interact with
Evolutionairy	users require new resources for interaction and new research oppertunities
Learning	Users require knowledge of the functioning of the system Users require knowledge of the functioning of the system to be easiliy obtainable
Replicabble	users require the modelling exercises to generate the same results under the same conditions
Traceable	users can learn and be inspired from research attempts of other participants
Trust	users require trust in the system AND users require trust in the resources made available by other participants AND users require trust in the use of their resources by others

Table 6.7: Users values, needs and desires

Value	Needs and Desires
Evolutionary	An evolutionary system requires the adding resources over time
Replicabble	Replicability requires version control and documenting the model runs
Scalable	A scalable system requires user management and
Secure	A secure system requires the application of a security policy
Trust	User must have trust in the system

Table 6.8: IT Managers, needs and desires

Value	Needs and Desires
Accessible	The application manager requires company policies set by lower tier or higher tier decision makers in order to make the system available to users
Scalable	The application manager requires policies from lower of higher tier decision-makers on the procedures to create and delete user accounts

Value	Needs and Desires
Secure	The application manager requires an application that sets access restrictions to exclude non-participants of the system The application manager requires operational control of the that is delegated

Table 6.9: Application Managers, needs and desires

By identifying the value-based needs and desires for the different roles that the stakeholders have in the MME+I the requirements for the system can be derived. These are presented in Table 6.10 - 6.15. The System Requirements Structure can be found in Appendix H (see Figure H.1).

ID	Requirement	Value
1	facilitate enduring data and model use and reuse	Enduring
1.1	Establish governance of the MME	Enduring
1.1.1	Document systems governance (and add to resources)	Enduring
1.1.2	Determine entry exit rules	Enduring
1.1.1.1	Enforce the rules of the game	Enduring
1.1.1.1.1	Add new participants accounts	Enduring
1.1.1.1.2	Remove former participants accounts	Enduring
1.2	Use private repositories for the resources of the MME	Enduring
1.2.1	Update the repository	Enduring
1.2.2	Back-up the repository	Enduring
1.2.3	Mirror the repository	Enduring

Table 6.10: Overview of systems requirements for the enduring value

ID	Requirement	Value
2	Facilitate evolutionary data and model use and reuse	Evolutionairy
2.1	Facilitate the entry of new participants (=extendable)	Evolutionairy
2.2	Facilitate the entry of new resources	Evolutionairy
2.2.1	Enable participants to upload new resources to the MME ME repository	Evolutionairy
2.2.2	Add resources' meta-data to meta information	Evolutionairy
2.2.3	Add data and information on model runs to the system	Evolutionairy
2.2.3.1	Add metadata on model run data to the system (or meta information) (=traceble)	Evolutionairy
2.2.3.2	Add model-run data to the system (=traceble)	Evolutionairy

Table 6.11: Overview of systems requirements for the evolutionary value

ID	Requirement	Value
3	support replicable decision-making processes	Replicable
3.1.	Adhere to scientific modelling practices	Replicable
3.1.1	Use models that are validated verified for their application	Replicable
3.1.2	Couple models only after a model auditing process	Replicable
3.2	Document data on model runs	Replicable
3.2.1	Document inputs, outputs other model run settings	Replicable

ID	Requirement	Value
3.2.2	Document data preparation, visualisation and analyses from model runs	Replicable

Table 6.12: Overview of systems requirements for the replicable value

ID	Requirement	Value
4	improve learning throughout the Dutch drinking water chain	Learning
4.1	Organise periodic meetings for knowledge sharing among participants	Learning
4.1.1	Record presentations on resources and add them to the knowledge database	Learning
4.2	Facilitate a discussion board to post questions and raise issues	Learning
4.2.1	Introduce a ranking system for contributions	Learning

Table 6.13: Overview of systems requirements for the learning value

ID	Requirement	Value
5	Facilitate engagement with the MME ME resources	Engagement
5.1	Provide access of participants to the MME ME resources	Engagement
5.1.1	Create an account for new participants	Engagement
5.1.1.1	Share account details with new participants	Engagement
	Facilitate empowerment of the participants	Empowerment
5.3	Use software environments that are suitable for multiple Operating Systems	Empowerment
5.3.1	Maintain a repository of the resources of the model (software, libraries and dependencies)	Empowerment
5.3.1.1	Add meta-information on resources dependencies to system knowledge	Empowerment
5.3.2	Update a repository of the resources of the model (software, libraries and dependencies)	Empowerment

Table 6.14: Overview of systems requirements for the engagement value

ID	Requirement	Value
6	Enable stakeholders to implement a secure system for resources sharing	Secure
6.1	Host the MME ME on a private server	Secure
6.1.1	Require users to login to the MME ME	Secure
6.1.2	Enforce a security policy	Secure
6.1.2.1	Change user password every 30 days	Secure
6.1.2.2	Apply two-factor authorisation	Secure
6.1.2.3	Delete an accounts of former participants	Secure
6.2	Implement a company policy on MME ME resource sharing	Secure
6.2.1.	Remove confidential information from resources before uploading to MME ME	Secure

ID	Requirement	Value
6.2.2.	Share resources without confidential information	Secure

Table 6.15: Overview of systems requirements for the secure value

6.5. Alternatives

Figure 6.2 shows a matrix with the developments and maturity possibilities for the MME+I.

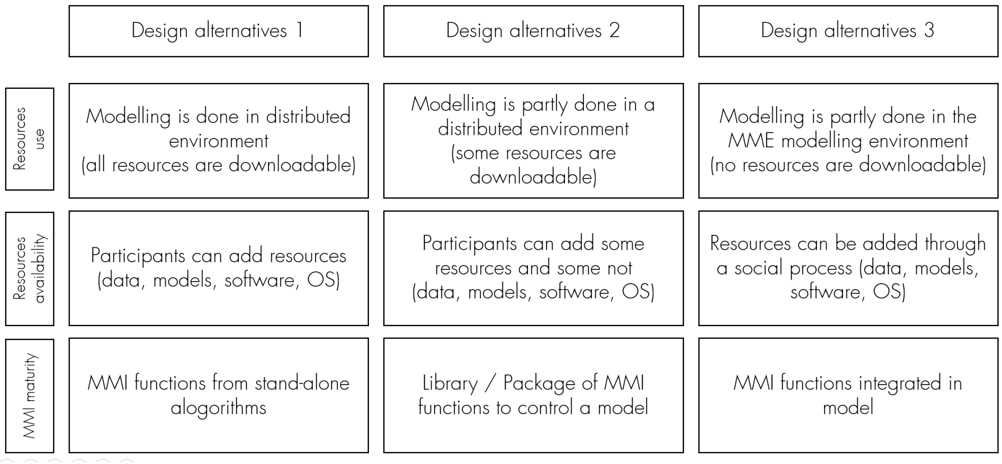

Figure 6.2: Design alternatives

7

Design Artefact: MMI Design

7.1. Design Requirements

For the design of the Logical Architecture of the MMI, three inputs were considered to generate the design for the MMI. First, the design characteristics that were identified in the literature review in Chapter 4. Second, the requirements that were identified during the Requirement Analysis and Specification from the previous chapter. Third, by determining all of the steps of a modelling workflow for a linear model workflow in order to determine the functional requirements. These inputs were then evaluated by relating them to the values of the MME+I. A mapping of the design characteristics found in the literature review of Chapter 4 to the design requirements for the MMI is shown in Figure 7.1. The linear workflow is presented in the next paragraph.

Design characteristic	Description of design characteristic	Req. ID	Requirements for the MME+I	MoSCoW
1, 5	Cultivation of an evolving set of resources that with some additional effort can be recombined and reconfigured for different purposes	1	Software, Model and Data repository	Must- have
2	Possibilities for model integration are not predefined, but emerge over time from ongoing development efforts	2	Enduring MME+I	Must- have
3	An extendable simulation environment	3	Participants can add resources to the MME ME	Must- have
6	The collection of modules refers to the above-mentioned combination of input data and model.	n.a.	Not applied, data and models will be stored in different repositories. However, meta-data on data and models with their inputs and outputs will be made available in a human-machine readable semantic wiki	Won't have
7, 10	Facilitate the linkage of models A script to pass information and execution commands	4	MMI	Must- have
8	Module repository to enable sharing of modules across different platform users	5	The MME ME contains a sofwtare repository to fasciliate modelling on different platforms	Must- have
9	A semantic wiki that details the functionality and inter-connectivity of modules	6	Implemented in the human-machine readable semantic wiki	Must- have
11	Publish systems modelling data with contextual metadata to enable data discovery and analysis		Not a requirement due to conflicts with Security requirement for the MME	Must- have
12	A version control system to facilitate synchronisation of code between	7	Version control for the repositories. In addition, a rationale is required when initiating a model run (workflow) via the MMI.	Must- have
13	Controlled vocabularies to relate terms across data sets and models	8	Vocabulary is part of the human-machien readable sematic wiki	Must- have
14	Visualize, edit, and compare networks, data sets, and scenarios in an online application	n.a.		Won't have

Figure 7.1: Design characteristics to design requirements mapping

7.2. Workflow for a model run

Models do not have to know of each other existence, but the MMI must have knowledge of the models. Which is acquired from the human-machine readable semantic wiki. Figure 7.2 depicts the workflow for a linear model run. The following steps are identified as part of a workflow or modelling process for an MME+I:

1. Make algorithms, (open-) data, models, scenarios available in the MME modelling environment.
2. Define the Research Question (narrative)

3. Operate/Instruct MMI to initiate modelling sequence
4. Execute modelling sequence
5. Gather data
6. Data processing
7. Data visualization
8. Data analyses
9. Upload results (of processing, visualization and analyses) to the MME modelling environment

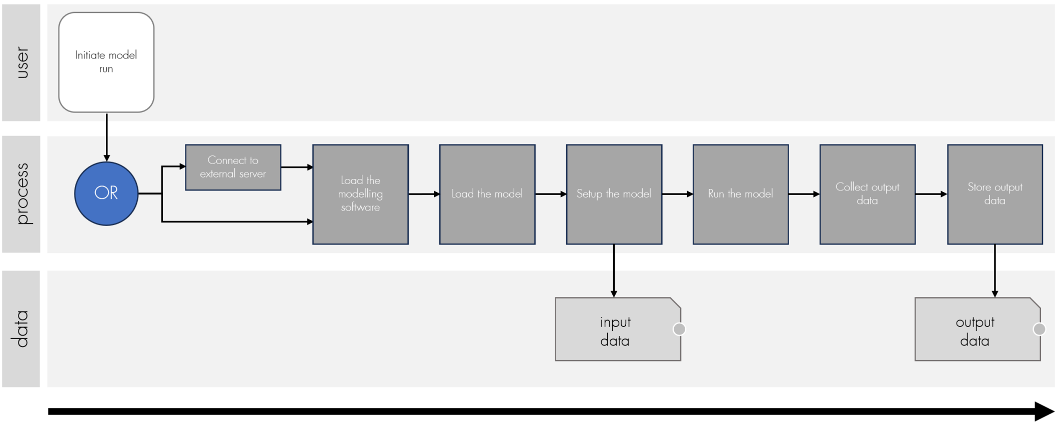

Figure 7.2: Model run workflow

Now that the design requirements are identified they can be applied to the design of the Logical Architecture.

7.3. Logical Architecture

Figure 7.3 shows the conceptual model for the MME+I for Oasen of which the MMI is a part of. It shows a closed system accessible only to its relevant stakeholders (participants). These participants have different roles in the system, as symbolized by the men/woman icons. Participants have personal knowledge and knowledge of the system both of which are part of a large body of knowledge. Participants interface with the MME Modelling Environment through distributed hardware and software. The MME Modelling Environment is an open system within the MME+I containing the available resources. The MME Modelling Environment is further specified in Figure 7.4 which presents the Logical Architecture for the MMI. Figure 7.4 shows MMI, Semantic Wiki and Repositories for the MME Modelling Environment including all of the required functions and possible interactions.

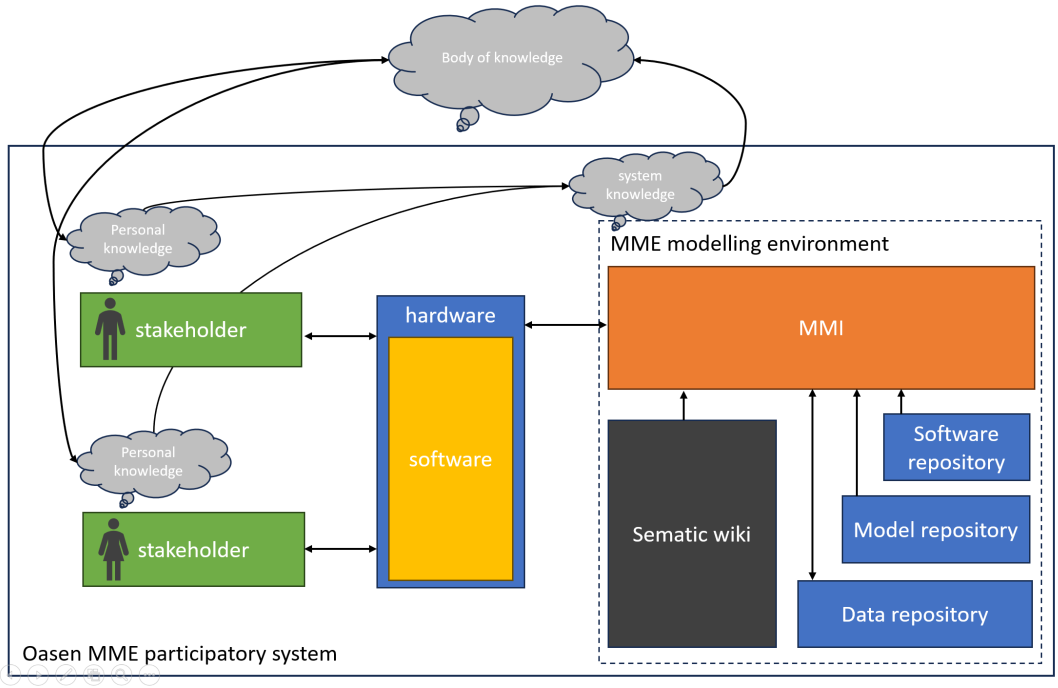

Figure 7.3: MME+I Conceptual model

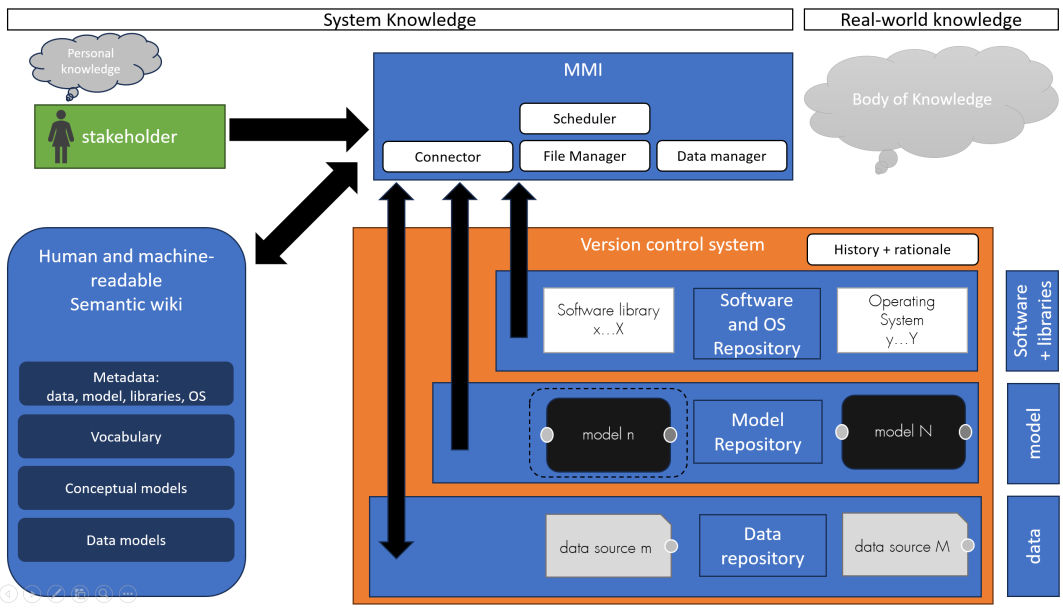

Figure 7.4: MMI Logical Architecture

8 Design Artefact: Multi-modelling Strategy

The previous chapter presented the logical architecture for the MMI. This enables using the models from the MME repositories through model coupling to answer research questions. This chapter applies the XLRM framework to create a modelling strategy to provide a Proof of Concept of the MME+I. The purpose of the modelling strategy is to aid in answering this thesis's main research question. This chapter also introduces the models to be linked with their inputs and outputs as a modelling workflow.

8.1. Futureproof DWDS

This thesis research aims to answer the main research question introduced in Chapter 1. The main research question is:

> How can a multi-model ecology aid the design of a future-proof drinking water distribution system?

In the context of this thesis report, a future-proof drinking water distribution system (DWDS) means a DWDS that is capable of performing its function throughout its economic life expectancy regardless of changing water demand patterns. These electronic water meters make it possible to give consumers insight into their drinking water consumption. The consequence is that this not only means installing the electronic water meter at the consumer but that the customer is periodically informed by the drinking water company about drinking water consumption, for example by using an app or a web page on which the consumer can log in.

8.2. Agent-based Modelling

”Agent-based modelling is a relatively new type of simulation technique to model complex systems of interacting autonomous agents” (Macal & North, 2010). Bonabeau states that agents have autonomy and heterogeneity and are active (2012). In an Agent-based model these agents interact by which they can affect each other and the behaviour of the system as a whole (Macal & North, 2010). Emergent behaviour is the systems' behaviour that occurs by the collective choices of interacting agents and is not programmed as behaviour in individual agents.”In many cases, ABM is most natural for describing and simulating a system composed of “behavioural” entities” (Bazghandi, 2012). Van Dam states that agent-based modelling is suited to model complex socio-technical systems (Dam et al., 2012). In 2020, KWR Water Research and TU Delft collaborated in an exploratory research endeavour to determine the suitability of Agent-based Modelling for applied research in the drinking water sector. Therefore, an agent-based model was developed for drinking water demand in a DWDS (Berendschot & Luttikhuizen, 2020; Blokker et al., 2020).

The ABM model is built based on the 10 steps according to Van Dam's methodology (Dam et al., 2012).

1. Problem formulation and actor identification
2. System identification and decomposition
3. Step 3:Concept formalisation
4. Model formalisation
5. Software implementation
6. Model verification
7. Experimentation
8. Data analysis
9. Model validation in Sect.
10. Model use

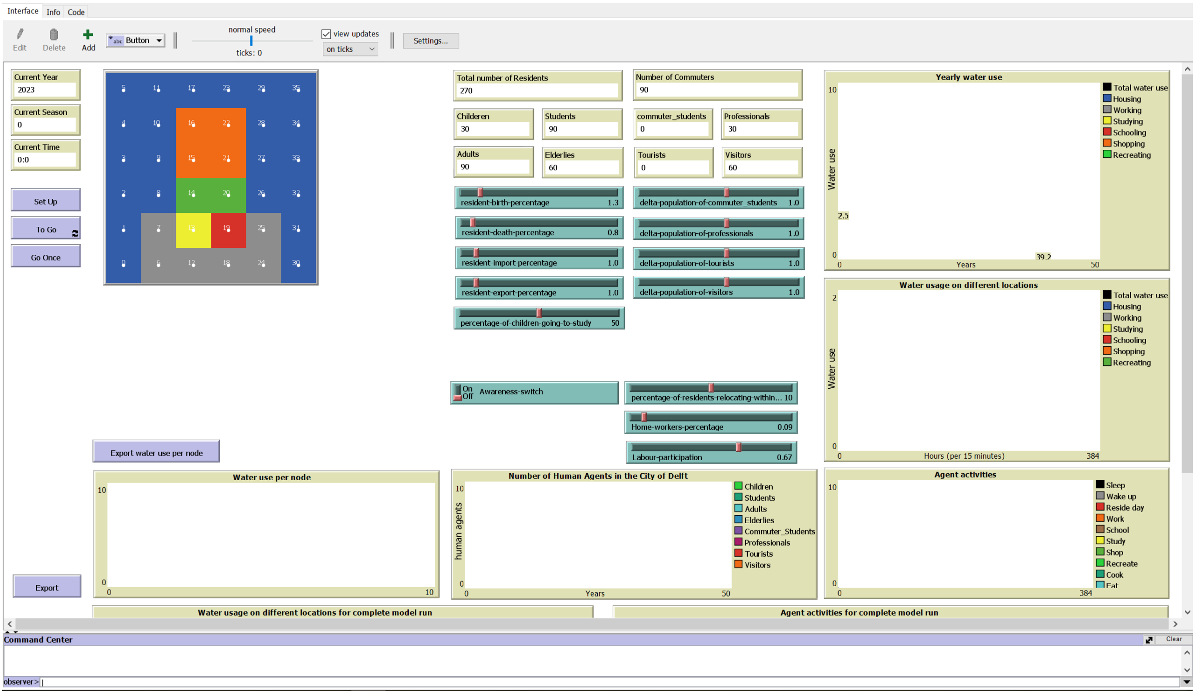

Figure 8.1: ABM Water Demand model in Netlogo

The ABM Water Demand model was developed to investigate whether an agent-based modelling approach "offers good opportunities for describing changes in drinking water demand over time and space so that a target structure can be designed with more confidence in the assumptions regarding drinking water demand" (Blokker et al., 2020).

Netlogo was used to model the demand for drinking water. The DWDS of the city of Delft is modelled on the basis of the nodes where a drinking water demand can occur. These nodes are located on a designated cluster of consumption. Six different consumption clusters have been defined: housing, working, studying, schooling, shopping and recreating. Agents can develop their activities on these clusters of consumption. There were 10 different activities: sleep, wake up, reside during the day, work, school, study, shop, recreate, cook and eat. Carrying out the activities is related to the water consumption that is possible per activity. For example, it is possible to drink a cup of tea or coffee while shopping, but it is not possible to shower in a place that is assigned for shopping in the model.

Within the agent-based model, 8 different types of human agents are applied to make up a municipality's community. These agents differ in age and activities that they deploy within the model based on their specific narratives/activities. These agents are: residents (children, students, adults and seniors), commuters (students and employees), tourists (overnight stays) and visitors (only present during the day). An important component of the model is the "development of the demography and the spatial distribution of water consumption, i.e. where are the agents located, and how this can change over the years. The user of the model can adjust the percentages for, among other things, birth, mortality, migration and labor participation. In this model, it is also possible to vary preferences regarding water consumption over time, so it is possible to turn awareness on or off, and to change the percentage of home workers" (Blokker et al., 2020).

The Agent-Based Model was developed in Netlogo. It consists of three sub-parts. Part one deals with the model's demography and simulates different demographic scenarios such as births, deaths, import and export out of a community. Within the simulation 8 different types of human agents are applied to make up a community of a municipality. These agents differ in age and activities that they deploy within the model based on their specific narratives/activities. The second part enables and structures the activities of different agents to a physical location in the simulation where agents have a specific water use. Thirdly, an urban zoning plan is used to facilitate the combination of location and activities of agents. The model is run for a period of 50 years (2020 – 2070) and simulates 4 days in each year per 15-minute interval. These four days represent the different seasons in the year with different water demand patterns (Blokker et al., 2020).

The original model was built to simulate water consumption in the city of Delft. The large number of nodes where a drinking water demand arises, in combination with approximately 110,000 agents and all the activities they can undertake during a day, leads to a large computational time. To prevent this during this thesis research, the original model has been adapted to a version with 36 patches with a node for water consumption on each patch as shown in Figure 8.1. The distribution of the patches is as follows: housing 61%, working 16%, studying 3%, schooling 3%, shopping 11% and recreating 6% as can be seen in Figure 8.2. In addition, another button was added to the model to enable the export of data for the water use per node. As in the original model, only aggregated data per patch per year was exported. The numbers in Figure 8.2 represent the nodes where the water demand is generated. The patches have different colours to denote the assigned activities: housing (blue), working (grey), studying (yellow), schooling (red), shopping (orange) and recreating (green).

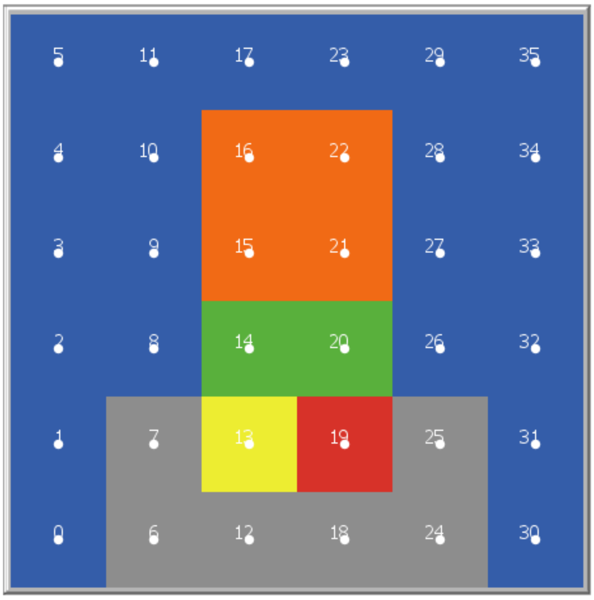

Figure 8.2: Patches and nodes for the adjusted ABM Water Demand Model

8.3. Data requirements

The adapted ABM model for the PoC use case does not require any input data. Data about the time agents spend is hard-coded in the model based on the Time Use Survey 2017 by the Sociaal Cultureel Planbureau. The same applies to the water consumption of the agents. The water consumption of the agents is based on Water use at home 2016 (van Thiel, 2016). The EPANET hydraulic model requires no other input data besides the water demand patterns generated by the ABM model and the drinking water infrastructure.

8.4. EPANET Hydraulic modelling

The global standard for hydraulic modelling of drinking water distribution networks is the EPANET program. EPANET is a public domain, water distribution system modelling software package developed by the United States Environmental Protection Agency's Water Supply and Water Resources Division (Rossman, 1999). An EPANET hydraulic model (see Figure 8.3) was developed for this thesis research. This is a small-scale model of a fictitious neighbourhood within the Oasen service area near the Rodenhuis treatment station in Bergambacht. The model contains a source and two transport pipes (for redundancy) to which 3 main pipes are connected. A total of 12 connecting pipes are connected to each of the 3 main pipes. These household connecting pipes supply the 36 nodes in total, which are the source of the drinking water demand in the model. The demand patterns for these nodes are generated in the ABM Water Demand model based on the total number of agents (scenario A: 391, scenario B: 387, scenario C: 392 and scenario D: 384) with an average of 10,5 agent per node).

The mapping of the nodes in the EPANET model corresponds to the layout of the assignment of the activities to the patches in the ABM model (see Figure 8.4). The coloured boxes at the bottom of Figure 8.4 relate to the 6 different types of activities from the ABM model and to the 6 different average demand patterns for the EPANET model. Table 8.1 provides an overview of the network pipes and their diameters. The network pipe types and their diameter are visualised in Figure 8.3: transport pipe with ⌀315 in red, transport pipe with ⌀200 in green, main pipe with ⌀110 in turquoise and household connection pipe with ⌀50 in blue.

Network pipes	Diameter
Transport pipe	315 or 200
Main pipe	110
Household connection pipe	50

Table 8.1: Distribution network characteristics

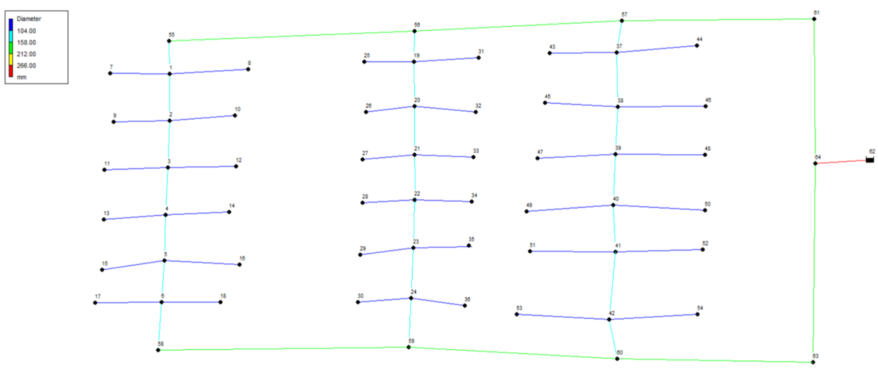

Figure 8.3: EPANET Hydraulic model for the PoC

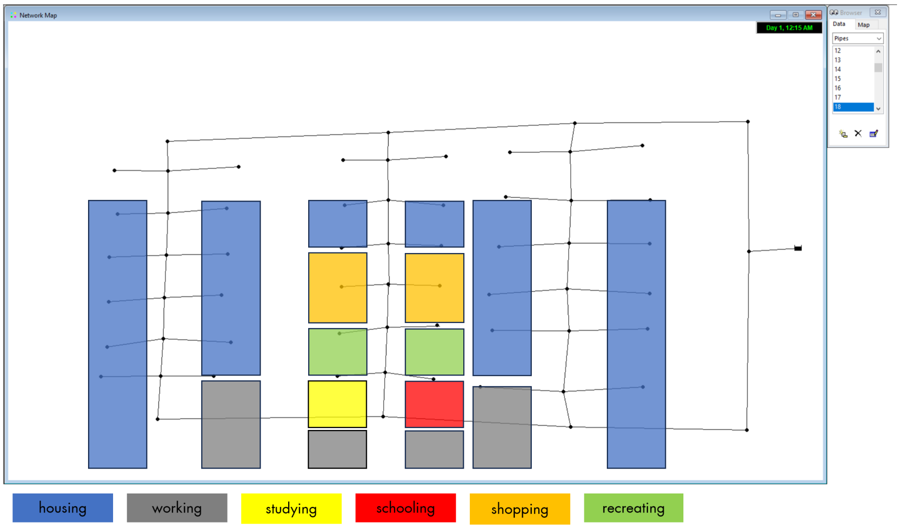

Figure 8.4: Mapping of ABM model patches to the corresponding nodes in the EPANET Hydraulic model

8.5. Multi-model coupling strategy

The models for the PoC use case and their respective inputs and outputs are presented in Figure 8.5. The model coupling is a linear approach where the output from the ABM model is used as input data for the EPANET hydraulic model.

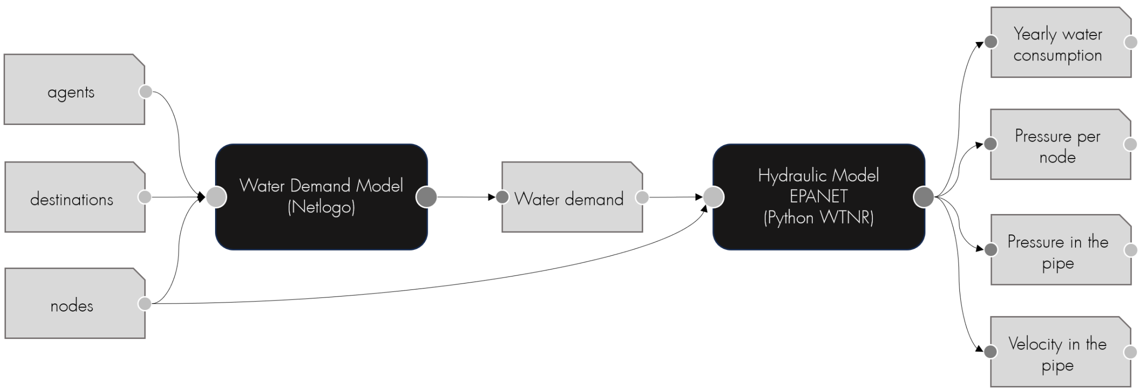

Figure 8.5: PoC Multi-modelling Strategy

9

Proof of Concept by a Use Case

In the previous chapter, the modelling strategy for answering the main research question was presented and explained. This is a simple, linear workflow in which the output data from the ABM model is used as input data for the EPANET model as water demand patterns. This exercise aims to investigate whether changes in the ABM model affect the hydraulic model. In this chapter, the assumptions, experiences and challenges with the 2 different model runs are presented.

9.1. The XLRM-framework applied

To connect the models in the PoC use case, an ABM Water Demand Model and an EPANET hydraulic model are available. By applying the XLRM framework to the main research question and the available models that operationalise the relationships of the system of interest, the following picture emerges.

External Factors (X): Possible effects of the impact of Climate Change

Policy Levers (L): Strategic investment decision-making regarding reducing, expanding or replacing parts of the DWDS of Oasen

Relationships in System (R): Development of drinking water demand for 50 years with a 15-minute interval.

Performance Metrics (M): Annual water consumption, pressure in transport and distribution network pipes, pressure at nodes for water use (household connections), velocity in distribution network pipes.

9.2. Operationalising the XLRM-framework

In order to answer the main research question the design of a future-proof DWDS is the focal point of this thesis research. For this purpose, use was made of existing water demand scenarios from a study into the robustness of drinking water distribution systems by means of stress testing of existing hydraulic networks (Agudelo & Blokker, 2014) The research has defined a total of 11 scenarios as is shown in Figure 9.1. Three scenarios have been selected for this thesis research. A scenario with the most water consumption, a scenario with the least water consumption and a scenario with a forecast for 2025. The ABM model has implemented water consumption based on drinking water consumption in the Netherlands in 2016 (van Thiel, 2016). Based on this selection, there is a basic scenario (scenario A) of approximately 120 litres per person per day. A second scenario is the forecast for 2025 (scenario B) based on 131.3 litres per person per day. The third scenario (scenario C) of an average of 69.3 litres per person per day is based on the premise that the toilet, washing machine and outside tap are not fed from the drinking water distribution system. The fourth and final scenario (scenario D) assumes a water consumption of 167.5 litres per person per day on a basic basis. The rationale for choosing these scenarios is to investigate whether there is an effect in the hydraulic model based on the extreme scenarios with the least and most drinking water consumption. This would demonstrate that the dynamic, multi-year prediction of the ABM model is suitable for use in a hydraulic model. In the current practice of hydraulic network modelling, stochastic variables are predominantly used to operationalise the water demand in the model, such as SIMDEUM (Blokker et al., 2020).

Sce.	Name	Characteristics
0	Now	Baseline: current situation, specific for each of the networks.
1	Pr.	Prognosis 2025.
2	RC	Regional Communities: per capita demand declines because the economic downfall results in (water) saving behaviour, coupled with decreasing population. The average age of the population increases.
3	SE	Strong Europe: Despite low economic growth, mobility increases due to open borders. Personal hygiene habits have changed with an increase in shower frequency. Water pricing based on real cost drives alternative water resources to be adapted on a larger scale; e.g. rain water tanks for watering the garden.
4	TM	Transatlantic Market: Population growth causes increases in drinking water demand. Innovations aim at luxury and wellness products.
5	GE	Global Economy: Economic growth causes increases in consumption. Innovations are aimed at luxury and wellness, people shower longer and water their garden more frequently to diminish the effects of climate change.
6	Dual	Toilet, laundry machine and outside tap are not supplied by DWDS.
7	Eco	Based on RC with innovative sanitation concepts. 100% adoption of 1 L flushing toilets.
8	Lux	Luxury, based on current situation with 100% adoption of luxurious shower, with a shower frequency of one shower per day.
9	GE+	Based on "GE" but with a shower frequency of one shower per day.
10	Leak	Based on "Now" with leakage of 20%.

Figure 9.1: Choice of scenarios for the PoC, scenario 1, 6 and 8 (Agudelo & Blokker, 2014)

After choosing the scenarios, the next step is to adjust the ABM model by implementing the 3 new scenarios in the code of the ABM model. For this purpose, a mapping has been made from the total water consumption per scenario to the options available in the ABM model to consume water per activity. This mapping can be found in Figure 9.2. For most of the water demand for end use the mapping is one-to-one. However, there are a few exceptions. First, the water for personal consumption is not an end use in the external scenarios (Agudelo & Blokker, 2014). For all of the activities combined in the ABM model, this adds up to a maximum of 1.2 litres per person per day, and this was not adjusted because of its small size. Second, the activity To Water the garden is attributed to the kitchen tap in the ABM model whereas the scenarios attribute this to the outside tap. No adjustments were made here because it is not of any influence on the model runs since the water demand in the ABM model originates from the activities of the agents and is related to the node where that activity occurs. Since the ABM model does not have the ability to relate water use to any endpoint other than the nodes on the patches in the model. The water demand for the end-use categories as defined in the scenarios was distributed over the activities of agents, taking into account the frequency of that activity. For example, for scenario B (Projection 2040 scenario) the total consumption of the shower is 55,4 litres. Since it is only possible in the ABM model to shower once daily, those 55,4 litres are assigned to the activity To Wake Up. When activities can occur multiple times a day, the total consumption for that day is divided by the number of occurrences and assigned accordingly to the activity. After assigning the end uses to the activities and frequencies the total water demand per day per person was determined. Deviations from the average daily water consumption as specified in the scenarios were attributed to the activity To Cook since that activity in the ABM model was unrealistic with 0.8 litres of water use.

9.3. Hydraulic modelling with ABM Water Demand patterns

The results of the model run of the EPANET model with the water demand input patterns from the ABM model are visualized in Figures 9.4 and 9.5. In order to say something about the performance of the hydraulic network, the network metrics are examined at two Points of Interest (PoI), as is shown in Figure 9.3. The first location concerns the transport pipe from the purification station to the first junction and is marked with a blue circle in the figure. The rationale for this is that changes in the water demand of the nodes affect the flow, pressure and velocity in the network. The cumulative of effects should

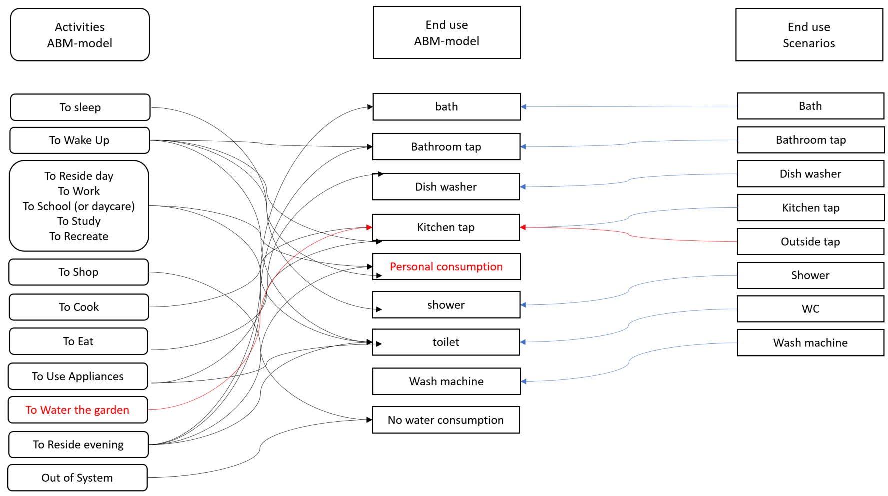

Figure 9.2: Mapping of water demand end use implementation methods for the ABM model and scenarios(Agudelo & Blokker, 2014).

then be visible in the transport pipe from the treatment plant as this is the source of the system. The second location that is analyzed is the location furthest from the treatment plant. This Point of Interest is marked with an orange circle in the figure. Here, the network metrics should be the lowest due to the distance to the treatment station. This location forms the benchmark for all of the other locations. If flow, pressure and velocity are sufficient here, they should be at least sufficient everywhere else in the system.

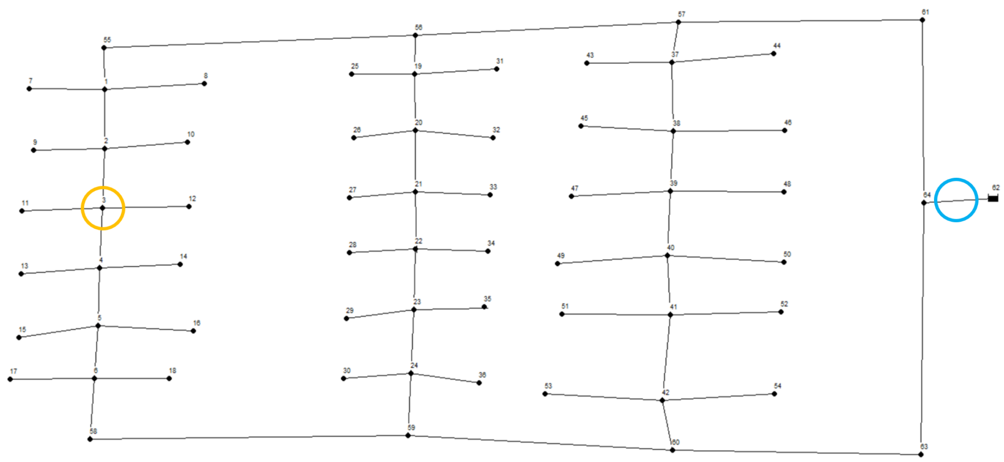

Figure 9.3: EPANET Hydraulic model with the Point of Interest

The results for the transport pipe are presented in Figure 9.4. This graph shows the flow in cubic meters per hour for the transport pipe. From this graph, the following conclusions can be drawn:

- Scenarios B, C and D display a water demand pattern that is consistent with water demand patterns for household demand, with a higher peak demand during morning hours and a smaller peak demand in the evening. The exception here is the performance for scenario A, where the model underperforms compared to the other scenarios.
- All of the scenarios generate different demand patterns to account for the difference between the water demand throughout the 4 seasons in a year as can be expected.
- Scenarios B, C and D display a water demand pattern consistent in relation to each other and what can be expected based on the input (average water use per person per day) for each of

those scenarios.

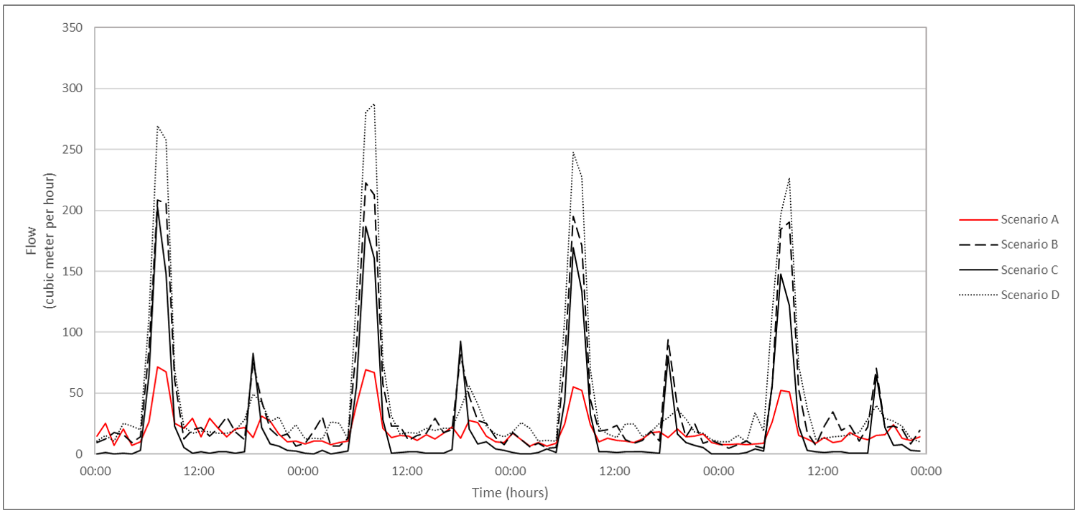

Figure 9.4: Flow in the transport main of the hydraulic model

The results for the second PoI are presented in Figure 9.5. This graph shows the pressure at Node 3, which is furthest away from the treatment plant. From this graph, the following conclusions can be drawn:

- The graph displays the same behaviour regarding peak demand as the previous graph.
- The same conclusions drawn from the previous graph regarding scenario A also apply here.
- Due to legal requirements, drinking water companies have to supply their drinking water demand with a pressure of 15 meters at ground level. For scenarios B, C and D the system can not meet that requirement at peak demand during springtime and summer days.
- Scenarios B and D cannot meet the pressure demand during peak hours in autumn and winter days.
- Scenario D, with the highest average water demand will lead to negative pressures in the system.

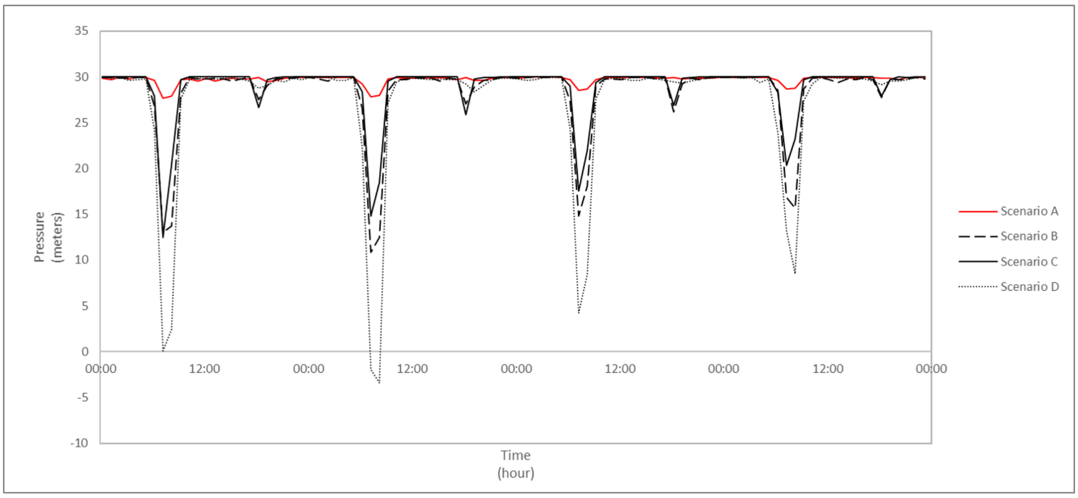

Figure 9.5: Pressure at Node 3

Applying the PoC use case shows that there is an effect of the results of the ABM Water Demand model on the EPANET hydraulic model. Based on the predictions of the EPANET model, it appears that negative pressures will occur in the hydraulic network in the case of Scenario D. In the daily practice of the drinking water company, water demand, water quality and supply pressure are the crucial parameters for business operations. To prevent the problem of negative pressures, three possible solutions are possible. First, it is possible to increase the pressures from the purification station. The minimum legally required pressure at the customer connection, at ground level is 150 kPa. Drinking water companies use their own company standard of of minimum of 200 kPa. It is possible to increase the pressure from the purification station to 600 kPa. Even higher pressures are not desirable in view of the maximum pressure that the distribution network can handle. At high pressures, the connections in the distribution network come under too much pressure and this can lead to leakage and outages. The second option is to only increase the pressure during the morning peak hours when the problem occurs. The same bandwidth in terms of pressure (200 - 600 kPa) applies as above with regards to the distribution network. Finally, it is possible to increase the dimensions of the network. Figure 9.6 shows that negative pressures do not occur when connecting pipes with a ⌀60 mm (instead of ⌀50 mm) are applied. Nevertheless, the pressure is still lower than the prescribed company standard of 200 kPa at ground level. In that case it would be advisable to increase the pressure from the treatment plant during peak hours to meet pressure requirement.

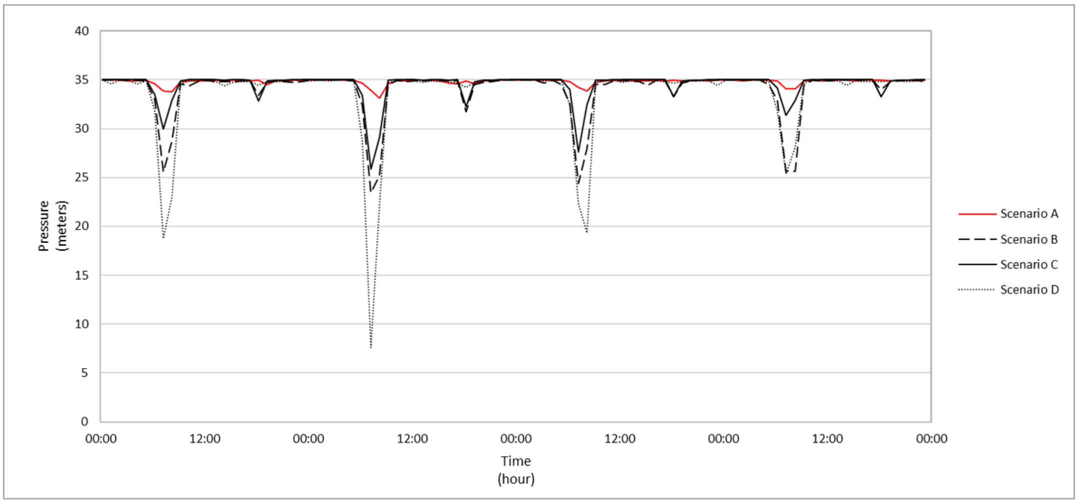

Figure 9.6: Pressure at Node 3 after adjusting the diameter of the connecting pipe from ⌀50 to ⌀60

This implies that the current system is under-dimensioned and that the drinking water distribution system needs to be replaced with pipes with a larger diameter.

10
Recent developments and a MME+I

The previous chapters presented the design of the MME and MMI. These designs are the result of two iterations of the discussed design methods. Both methods and the XLRM framework place stakeholders at the centre of the formulation of design requirements. A real-world implementation of a design process with stakeholders to design an MME+I for the drinking water sector would require an extensive social process. This social process should initially bring the various stakeholders together. Subsequently, the stakeholders should have a sufficiently shared view of the problem of the lack of an MME+I. And a desire to collaborate to tackle that problem. Finally, stakeholders should make a long-term financial and time commitment to designing an MME+I. That process was omitted during this research because the social process of designing and realising an MME+I exceeds the time span of thesis research. By using the PSD methodology based on values, specific design requirements for the stakeholders can be included in the design process. This makes it possible to design a Participatory System without the participatory process. The designs presented in this thesis can be applied in subsequent design iterations in a process with active stakeholder involvement.

10.1. Multi-Modelling for Integral Decision Making

An example of a social process that has produced an MME+I is the Multi-Modelling for Integral Decision Making (MMvIB) project by Matthijssen and Werkman (2023). The multi-model project is an initiative by TNO to make multi-modeling available for the Dutch energy sector based on a multi-model ecosystem idea similar to Bollinger's MME (2015). A strong concept with this approach is the idea that a model does not know and does not need to know that it is part of a multi-model. This idea has not been presented as such in this thesis, but has been an implicit assumption by choosing an MME+I for the existing models in the drinking water sector. Table 10.1 compares the concepts of the MMvIB and the MME+I Oasen concepts as applied in this thesis. In addition, Table 10.2 provides an overview of the MMvIB concepts and the current operalisation of the MME+I for Oasen.

MMvIB concepts	MME+I Oasen concepts
A model doesn't know and doesn't need to know that it's part of a multi-model	Make use of the existing models that are currently used in the DWI
A model doesn't need to be open (source) to become part of a multi-model	Models and data can be confidential
An external software component will take care of the right order of model execution	Use an MMI to orchestrate the model run
Data exchange between models is standardised	Data exchange between models is standardised when applicable

Table 10.1: MMiVB and MME+I concept comparison

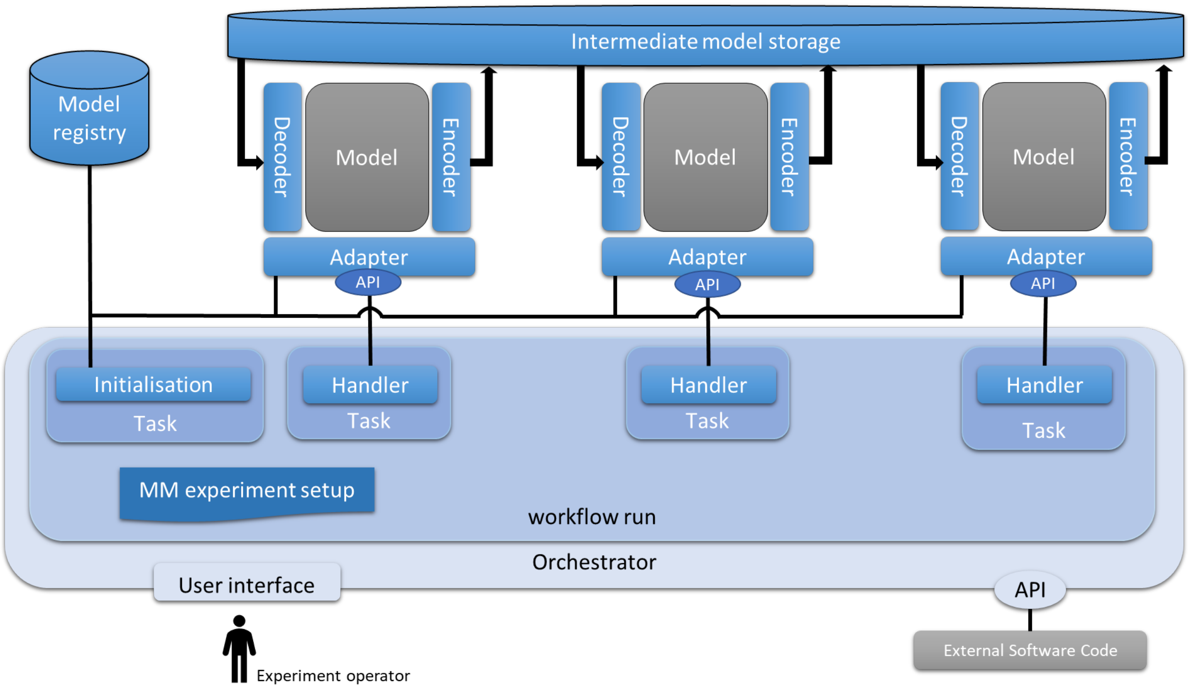

Figure 10.1: MMvIB High Level Architecture (2023)

MMvIB Architecture	MME+I Oasen Architecture
The orchestrator: The orchestrator takes care of orchestrating a workflow in which multiple models are executed in a particular order	Orchestrator or Event-handler
Models: The models perform the real calculations that are required to answer a certain question	Existing models in the MME ME that require data inputs and perform calculations for output data
Model adapters: The model adapters make sure the orchestrator can interact with the models	Python libraries for model interaction or Python code in Jupiter Notebooks
Model registry: The model registry keeps track of which model (adapters) are there and enables the orchestrator to find a model	Model repository and model meta-data, semantic wiki
Intermediate model storage: The intermediate model storage is used to store data that goes into a model or comes out of a model. This can be an intermediate or final result.	Currently CSV-files

Table 10.2: MMiVB and MME+I architecture comparison

10.2. Basic Model Interface

”The Basic Model Interface (BMI) is a library specification created by the Community Surface Dynamics Modeling System (CSDMS) to facilitate the conversion of a model or dataset into a reusable, plug-and-play component. Recall that, in this context, an interface is a named set of functions with prescribed arguments and return values. The BMI functions make a model self-describing and fully controllable by a modeling framework or application. By design, the BMI functions are straightforward to implement in any language, using only simple data types from standard language libraries. Also by design, the BMI functions are noninvasive. This means that a model's BMI does not make calls to other components or tools and is not modified to use any framework-specific data structures. A BMI, therefore, introduces no dependencies into a model, so the model can still be used in a stand-alone manner" (Hutton et al., 2020; Peckham et al., 2013).

The BMI is a standard interface implemented in four programming languages and can be applied to numerical models. This library specification makes it possible through software refactoring (altering the existing algorithms of a numerical model) to interface with the model by calling functions by a script or software program. Compared to the MMI the "problem" of interfacing with the models is solved by adjusting the models themselves. Whereas in, the MME+I the notion is that the models remain unaltered and the MMI requires the flexibility to deal with a diverse set of models and thus a diverse set of ways of interacting.

10.3. Waterverse

Waterverse is a European Union co-funded project of 15 research institutions, non-profit organisations and drinking water companies that "aims to develop a water data management ecosystem that will make data management practices and resources in the water sector accessible, affordable, secure, fair and easy to use" (Waterverse.eu, 2023).

The rationale for the Waterverse program comes from the challenges that the participants describe. "The actual use of data in the water sector is hindered by strong data ownership approaches (data retention) due to the perception that data sharing is a risk for confidentiality leakage and for other security aspects of critical infrastructures, unclear business models, poor quality of data (not reliable, too scattered, not usable, not available in real-time and not shareable) as well as the fragmentation and conservative attitude of the water utilities end-users."(Waterverse.eu, 2023)..

"The Waterverse mission is to develop a Water Data Management Ecosystem (WDME) for: making data management practices and resources in the water sector accessible, affordable, secure, fair, and easy to use improving the usability of data and the interoperability of data-intensive processes lowering the entry barrier to data spaces enhancing the resilience of water utilities boosting the perceived value of data and therefore the market opportunities behind it"(Waterverse.eu, 2023)..

The Waterverse approach entails "actively engaging end-users and stakeholders to assess the main gaps and challenges the water sector and contribute to quality European data spaces. Identify, extend, and integrate a wide set of data management tools to implement the Water Data Management Ecosystem (WDME). Comprise building blocks, tools, and methods to ensure security and energy efficiency of the whole WDME. Setup and demonstrate the WATERVERSE WDME in a real environment with relevant and diverse case studies involving water sector stakeholders from 6 countries. Set clear and measurable indicators for assessing the fairness of data in water-related data spaces. Ensure the viability and sustainability of the WATERVERSE WDME, as well as its replicability, scalability and business applicability" (Waterverse.eu, 2023)..

The Waterverse program is interesting for Oasen's MME+I and the Dutch drinking water sector because (1) The program concerns data management and which is also a topic in the MME+I, (2) as has also become apparent from the Literature Review in Chapter 3 (3) the problem has already been identified by other parties who want to work together to solve the to solve (4) it is easier to join an existing initiative instead of reinventing the wheel yourself (5) The project has already been financed and (6) KWR is involved as one of the participants.

11

Discussion

11.1. Research limitations

The biggest limitation of this thesis research into an MME+I for the Dutch drinking water sector is that the design process for this Participatory System took place without involving all stakeholders. In practice, this would mean that the Management Team of Oasen and other drinking water companies, team managers from various departments (Asset Management, Technology and IT Development), the Environment Manager of Oasen, as well as staff from the Asset Management and Technology departments, people from KWR and TU Delft should be involved. The time commitment of all those people alone would make this an expensive exercise in advance. In that sense, the greatest limitation is also the greatest strength of this research. Using the PSD methodology, it is possible to arrive at a design for an MME+I for Oasen and the drinking water sector with significantly fewer man-hours. And now that there is a design for an MME+I, we can build on this.

Another limitation of this thesis research is that it is a design process. Although the design process is documented step by step in this thesis, it is not replicable. Since that is a characteristic of design processes in general. On the other hand, the choices and considerations during the design process are transparent by documenting them. This makes it possible to return to and re-discuss previous design choices in an iterative follow-up design process.

Another important limitation arises from the qualities and skills of the designer of the MME+I. As a result, the focus of this thesis research is on the application of an ABM model built with Netlogo, an MMI based on Jupyter Notebook and Python as a programming language. In practice, this means that a wide range of design choices (other models in other programming languages) were ignored quite early in the process of designing this thesis research. On the other hand, designing an MME+I with several experts from the drinking water sector of the stakeholders in scope was discussed during the semi-structured interviews. During those conversations, no information came to light that another method would produce better results. An EPANET model was also developed during this thesis research due to the author's lack of experience with hydraulic modelling.

Another limitation concerns the chosen design methods PSD and SRE, which are value-based. A value-based approach during a participatory approach could lead to a shared vocabulary for the participants where the word's meaning for each participating stakeholder corresponds or at least largely corresponds. In a participatory design process with solely a designer interacting with stakeholders without stakeholders interacting among themselves, there is no shared vocabulary from a social process. In addition, issues relating to the authority of the process or its outcomes are also not addressed.

Another limitation of the thesis research relates to the models used for model coupling. The ABM model generates water demand based on demographic developments and drinking water use. The agents do not influence each other in the model. Furthermore, there are no effects of policy measures such as a subsidy on economical drinking water equipment such as a water-saving shower. Travel time is not included in the model. Furthermore, the effects of the weather on drinking water consumption or climate change have not been modelled. One of the learning points of the modelling process of the ABM model is that drinking water demand is influenced by so many factors that it is impossible to summarize them all in one model. It would be better to identify all those factors to create reusable models and apply those in an MME+I to model drinking water demand. The EPANET model is a small-scale model specially developed for use in the PoC use case. It is preferable to use a model that is also used in practice by a drinking water company. However, to use Oasen's hydraulic model for this would mean that the ABM model would have to model approximately 808,160 inhabitants who use 369,570 drinking water consumption nodes.

11.2. Discussion

Assumption for the literature selection

The literature review in Chapter 4 selected the literature on the assumption that if a second article cites the first article there is a good chance that the concepts and definitions are applied similarly. This proved to be a difficult statement to uphold. First, those articles that adhered to the exact same definition came from the same author as one of the selected articles or came from a co-author who worked on the same project. All of the other authors engaged in the same definition ambiguity in one way or another. What was interesting to see from the reviewed literature is the cross-pollination into other research fields.

Effortless model-linking?

In the PoC multi-modeling use case, the ABM model had to be adjusted because the water demand had to be reported per node to be mapped to the nodes in the EPANET model. Bollinger and Evins at HUES have also used models that have been adapted for use in an MME+I (2015). That raises the question of how realistic it is to expect models to be couplable and to what extent. In conclusion, if you want to connect models together, it is important to realize that an audit process should always precede this in which you look at which inputs and outputs a model has. And what operations are needed to link model A to model B? If that knowledge is documented, then in itself it has been a useful activity.

What is the added value?

The added value of an MME+I for Oasen lies in the fact that you can share and use the models you have with stakeholders. An MME+I only for internal use at Oasen between different departments makes less sense because such a system is overkill. Because in practice, colleagues seek each other out to answer research questions and use the models they already have or develop new models themselves. However, there is not always time for that. Then, it can be useful if you have access to a repository of verified and validated models that already exist. However, then you are not utilizing the learning capacity of an MME+I. Another approach could be to implement the MMI and repositories and first cultivate the MME+I internally, after which you open it up to other stakeholders. However, then you run the risk that you now have a system with so many lock-ins and legacy that it no longer has the flexibility to connect with the attempts and models of others.

Why hasn't a MME+I materialised?

This thesis research has made it clear that there are already many initiatives in the field on collaboration on model building, data exchange, and data-model exchange for the drinking water sector. This implies that there is a shared sector-wide vision regarding the problems and challenges for the sector. This thesis research was created based on the idea that if you built it, they will use it. On the other hand, it is arguable that if there had been a need for an MME+I, it would have materialized. The answer to this argument is that people should know that an MME+I is possible. In a sector that relies on well-proven methods, because water must always come from the tap, it is perhaps not obvious to expect major innovations in the field of computer simulations.

Or is it materialising in a different form?
Multi-modelling in the drinking water world is already on the rise; look at all the developments in the field of implementing Digital Twins. However, the focus seems more on business operations, while an MME+I focuses more on exploratory research. Digital Twins are developed by applying a project approach with a budget and the design requirements that are specified upfront. A Digital Twin aims to provide insight into the operations of one or several business processes and the effects that can occur when a certain parameter is adjusted. The type of insight that is required can be characterised a an ”Known Knowns” (see Figure 11.1). Meanwhile, MME+Is can provide insight into the ”Unknown Unknowns”, which were not foreseen or expected upfront.

	Known	Unknown
Known	Known Knowns	Unknown Knowns (Mistakes)
Unknown	Known Unknowns (Multiple classifications)	Unknown Unknowns

Figure 11.1: Knowns and Unknowns matrix adjusted from (Combs, 2021)

12 Conclusions and Recommendations

12.1. Answers to the Sub-questions

This thesis report started by introducing the main and sub-research questions for this exploratory research. These will be presented here in order to present the results. First, the sub-research questions will be discussed followed by the main research question.

The four sub-research questions are:

1. Which models and modelling methodologies or techniques are currently used at Oasen?
2. What are the design characteristics of operational MMEs?
3. What are the design specifications for an MME for the DWI?
4. What lessons can be learned from an iterative Design Science approach for the design of an MME+I?

12.1.1. Sub-research question 1

The first sub-research question led to developing a Model Assessment method for model meta-data as presented in Chapter 5. The semi-structured interview with colleagues at Oasen who use models led to an inventory of the 10 most important models frequently used in the operations of Oasen. The Model assessment method was used for those models. From that exercise, the following can be concluded:

- The 3 most used types of models are hydraulic models, process operations models and water demand models.
- Modelling is very important for short-term interventions in the water purification process and operations at the treatment plants of Oasen.
- Models are used to optimise processes for the balanced management of the system. These models try to optimise a steady production flow with the expected demand and the available capacity for storage.
- Models are applied for medium-term decision-making, e.g. the renewal of sourcing wells.
- Models are used for strategic long-term planning, e.g. the water demand forecasting models. These are used to determine the systems' capacity for the long-term.
- The Model Assessment method can be applied for the meta-data but it is often difficult to get all of the specifics of a certain model.
- Models applied at Oasen can be internally and externally developed for daily operations and incidental research questions.
- Models as applied to Oasen are single-use, standalone models with no interfaces to engage with other models.

- It proved difficult to ascertain all of the required information for the Model Assessment method either due to a lack of knowledge or due to propriety issues.

12.1.2. Sub-research question 2

A literature review in Chapter 4 answered the second sub-research question. This review gave insight into design characteristics for operational MMEs. These were used in Chapter 7 for the design of the MMI. Which was presented by its Logical Architecture in that chapter. In addition to the presented findings in Chapter 4 on the concepts and terminology, design characteristics and architecture the following conclusion can be drawn from the literature review:

- The literature search resulted in a number of review papers which are excellent at providing insight but less suited for the design characteristics of operational MMEs and their architecture of design considerations.
- Multi-model ecologies as defined in this thesis report haven't materialised yet in the field of Water Resource Management.
- Several authors do point out a need for model coupling, multi-modelling or multi-model ecologies because of the expected advantages of bringing together experiences from different research fields to better model the complexity of a research field, to better engage with decision-makers or stakeholders or for the reason of conducting scientific research in a transparent matter to engage the public.
- In literature the idea of an MME is presented as a "place" where data and models are brought together and from where an emergent system of multi-modelling will automatically come into existence. So, the idea of an MME as a product of a design exercise is not explicitly present. However, some authors have used conceptual models and designed an architecture for the purpose of multi-modelling.
- However, no insight into the design process or alternative selection for these architectures has been published. There is a lack of knowledge on the design process and the design considerations and alternative selection for the design of an MME+I.
- Furthermore, seven of te reviewed articles describe design characteristics for an MME.
- The literature review yielded 14 design characteristics for an MME+I.
- It also provides insight into the distinct roles stakeholders can play in an MME+I.
- Even fewer articles mention an MMI explicitly. However, one of the articles explicitly describes the use of a script to pass information between models and execute commands (Evins, 2017). This can be interpreted as a low maturity or basic MMI functionality. However, from the reviewed literature it can be concluded that there is a lack of attention to the specific requirements of MMI functionality in the reviewed literature.
- One item of concern is the continuation of an MME+I. The original article that introduced HUES was published in 2015. More articles were published thereafter such as an article from Evins in 2017. However, although certain models in the HUES platform are still available on Github, the HUES web page is inaccessible after the initial homepage and has not been maintained.
- An important finding of this literature review is the matter in which models require adjustments or adaptation in order to be usable in an MME+I. In an ideal MME+I all types of models can be added for use and reuse. In practice, this is not always a feasible vantage point since some of the models had to be adjusted in order to be used for multi-modelling. This practice raises all kinds of questions with regard to model validation and verification and overall applicability after the adjustments are made. Applying a model outside of its intended use is not by definition wrong. However, it does require proof of the altered model's validity, which can require quite some effort. This burden can be alleviated if the model is well-documented. However, this is not always the case. In order to move forward practising good modelling practices (Nikolic et al., n.d.) in the field of WRM scientific research is advisable.

12.1.3. Sub-research question 3

The third sub-research (What are the design specifications for an MME for the DWI?) question was answered in Chapter 5, where the PSD methodology was applied in order to generate a design for the MME+I for Oasen. A conceptual model of the design was presented in Chapter 7 with the Logical Architecture for the MMI.

12.1.4. Sub-research question 4

The final sub-research question (What lessons can be learned from an iterative Design Science approach for the design of an MME+I?) is answered in this paragraph. The lessons learned from an iterative Design Science approach are:

- An iterative approach relaxes the design process because there is no need to have to get it right the first time. Since there is an opportunity to reconsider every decision in the next step.
- An iterative approach implies that all steps of a phase are applied before moving to the next phase. But since design is capricious in nature, it can occur that a designer jumps from one task within a phase to another task in another phase without completing the iteration.
- IN theory most of the workload can be attributed to the first iteration. Sequential iterations require less work.
- However, due to the capricious nature of design processes the opposite can be true.
- Designers can get stuck. That happened in this thesis research when all of the values had to be redefined which meant that the requirements had to be re-evaluated and a new System Requirement Structure had to be implemented.
- It can be challenging in an iterative design process to organise a workflow that keeps track of changes in all the phases of the iterations

12.1.5. Conclusions from the Model Assessment Method

The application of the Model Assessment Method to the models used at Oasen has provided insight into the challenges of loosely coupling single-use models. The water demand is generated per node in the ABM Water Demand Model. Where a node corresponds to a connection (domestic or business). This is the smallest resolution of the water demand in that model. In Oasen's hydraulic model, there is an aggregated water demand from a number of connections. The smallest variation in water demand here is a certain pipe segment with a minimum of 1 connection and an -in theory- infinite number of connections. This makes it practically impossible to use (part of) the Oasen hydraulic model for the PoC use case.

12.1.6. Conclusions from the PoC use case

From the multi-modelling coupling exercise the following intermediate conclusions can be drawn:

- The water demand patterns from the behavioural-driven ABM model demonstrate an effect in the EPANET hydraulic model.
- Scenarios B, C and D display a water demand pattern that is consistent with water demand patterns for household demand, with a higher peak demand during morning hours and a smaller peak demand in the evening. The exception here is the performance for scenario A, where the model underperforms compared to the other scenarios.
- All of the scenarios generate different demand patterns to account for the difference between the water demand throughout the 4 seasons in a year as can be expected.
- Scenarios B, C and D display a water demand pattern consistent in relation to each other and what can be expected based on the input (average water use per person per day) for each of those scenarios.
- Due to legal requirements, drinking water companies have to supply their drinking water demand with a pressure of 15 meters at ground level. For scenarios B, C and D the system can not meet that requirement at peak demand during springtime and summer days.

- Scenarios B and D cannot meet the pressure demand during peak hours in autumn and winter days.
- Scenario D, with the highest average water demand will lead to negative pressures in the system. This implies that the current system is under-dimensioned and that the drinking water distribution system needs to be replaced with pipes with a larger diameter.
- Coupling an ABM model to a hydraulic model is a novel approach for Oasen.
- Due to the limitations of the models further research is needed to explore the possibilities of the ABM model and the effects in real-world hydraulic models.
- Further research could explore the range of scenarios from a behavioural perspective and the implications for the design of future drinking water distribution systems for the possible effects from climate change on the DWDS.

12.2. Answers to the Main Research Question

The main research question is ”How can a multi-model ecology aid the design of a future-proof drinking water distribution system?”

In this thesis research, an MME+I was designed and implemented in a PoC use case for multi-modelling and demonstrated that the outcomes of an ABM-model affect the EPANET hydraulic model's performance. It provided insight into how changes in water demand from scenario studies can affect strategic investment decisions for drinking water utilities.

12.3. Thesis contribution

This thesis research has yielded the following results:

- A literature review on the design characteristics of operational MMEs that provided insight into a knowledge gap on design considerations and alternative selection for operational MMEs.
- Presented the design characteristics for operational MMEs.
- The Model Assessment Method to provide insight into model meta-data and to facilitate model coupling.
- Stakeholder interviews to determine model use at Oasen and provide insight into user requirements for the design of the MME+I.
- Presented the design requirements for an MME+I
- The design alternatives for the use of the resources in the MME+I, the resources availability and the maturity of the MMI.
- The conceptual model for the MME+I design.
- Presented the design requirement and logical Architecture for an MMI.
- A PoC use case strategy based on the XMLR-framework.
- A novel approach for Oasen by coupling an ABM water demand model to a hydraulic model and proving its usefulness for business operations and future developments of the drinking water distribution network.
- Presented an overview of relevant developments in data and modelling for the Dutch drinking water sector.

12.4. Recommendations

This paragraph will present the recommendations for future development of the MME+I and research.

- Continue iterating the MME+I design but involve stakeholders.
- Adopt the MMVIB High-Level Architecture as a starting point and adjust were required based on the results from the iterations with stakeholders.

- Explore the possibilities for Participatory Modelling with stakeholders in the subsurface in order to prevent disturbances in the subsurface due to ill-aligned maintenance work.
- Explore the possibilities for Participatory Modelling with stakeholders to create new opportunities for water sourcing for the treatment plants.
- Explore the possibilities for the modelling of state-of-the-art DWDS.
- Encourage domain experts to develop consistent models, for example, for demographic developments, so that the different stakeholders that operate in the subsurface can use that model through a loose model coupling. And base their investment decisions on the same expected demographic developments.

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A

Definitions

Term	Definition
Conceptual model	A representation of a system that displays the concepts of that system and their mutual relations
Data	Structured or unstructured collection of inputs for a model.
Data models	Models that contain the entities and relations for structured data.
Formalism	Modelling framework containing the basic assumptions, ways of thinking, and methodology.
Method	A method is a solution-oriented working method in which techniques and tools are used as aids.
Methodology	A methodology is a coherent set of methods and techniques that can be applied together to solve a problem.
Model	Description of an abstraction of a real-world system.
Modelling	The act of constructing a model by interrelating the important concepts of a system of interest (Johannesson & Perjons, 2021)
Operational model	An operational model is a model that specifies the concepts and relationships in the model so completely that it is possible to convert this model into a computational model without additional information.
Paradigm	Set of methodologies within a research field that present a coherent view on that research field and its methods and techniques.
Technique	A technique is a collection of interrelated skills used to perform a specific task.
Tool	A tool is an aid or tool that supports carrying out the activities associated with certain techniques.
Water Resource Management	Activities of drinking water companies throughout the drinking water chain for the operational management of their sourcing and end-product

Table A.1: Terms and Definitions

B

Literature Review

This chapter describes the search methodology for state-of-the-art literature to explore a peer-reviewed body of knowledge with regard to the application of a multi-model ecology for the drinking water industry. In the following section, the main concepts related to this application and the search methodology for the literature are presented.

B.1. Main concepts and Methodology

B.1.1. Main concepts

”A model is an abstraction or simplification of an artefact. a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process” (DoD, 1998) And a ”multi-model is a set of interacting models” (Camus et al., 2015). Multi-models are typically used to research processes in complex systems (Goldspink, 2000). Multi-modelling is about co-simulation or interaction between the models (Gomes et al., 2018). A multi-model ecology (see Figure B.1) is an interacting group of models and data sets co-evolving with one another within the context of a dynamic socio-technical environment (Bollinger & Evins, 2015b). In a multi-model ecology, a multi-model interface is applied in order to facilitate communication between models and data sources within the multi-model ecology. A multi-model interface (see Figure B.2) can broadly be defined as encompassing the notions of a software interface (API), a structured data representation, a software daemon and a structured social process (Nikolic et al., 2019).

A drinking water company is an organisation whose main business activity is the production of fresh drinking water. The chain of processes from sourcing, production, transport, storage and distribution to the end-consumers are fulfilled by a single company for a specific geographical region (see Figure B.3). This drinking water chain brings forth the fresh drinking water that is supplied to end-customers via a DWDS. Drinking water companies fulfil all activities in the drinking water chain from sourcing to distribution and metering. A drinking water infrastructure (DWI) can be characterised as a “system that consists of complex interactions of assets and social actors in the technical network (socio-technical system) and the water resources in the geophysical environment (social-ecological system) making DWI systems a system of systems (SoS)” (Kloosterman & Van der Hoek, 2020).

B.1.2. Literature review methodology

The starting point of this LR was the methodology as described by Van Wee and Banister in their article, “How To Write a Literature Review Paper?” (Wee & Banister, 2016). A search methodology was applied in order to collect a body of literature to explore the topic. The main challenge with this LR lies in the presupposition that a multi-modelling approach with an MME/MMI has not been applied to research in the DWI. So, the aim here is to perform a broad search into the available peer-reviewed literature. For that purpose, two main search approaches were applied.

First, a search was conducted based on relevant keywords and logical expressions with three differ-

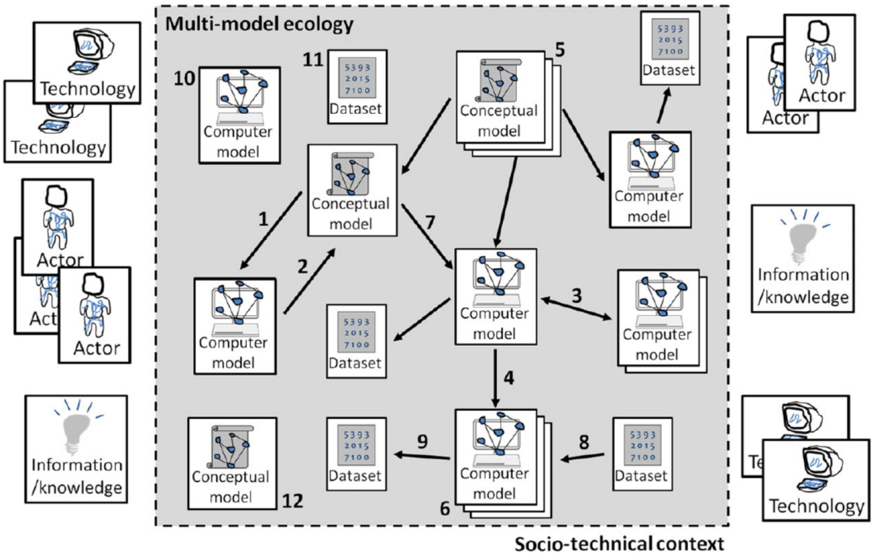


Figure B.1: Multi-model ecology (Bollinger & Evins, 2015b)

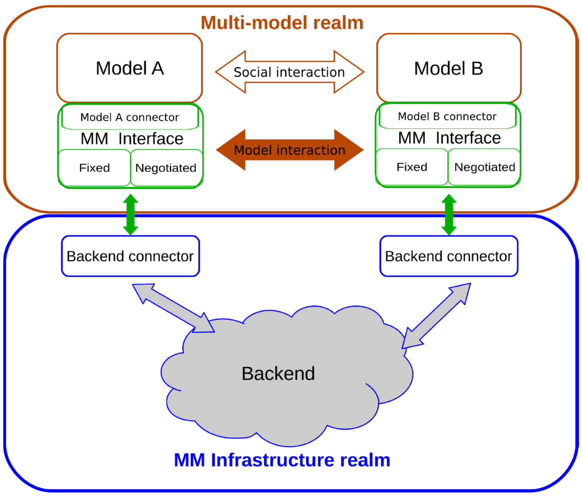


Figure B.2: Multi-model interaction in (red), interfaces (green) and infrastructure (blue) (Nikolic et al., 2019)

ent scientific databases (Scopus, Science Direct and Web of Science (see Table C.1 in Appendix C). Secondly, a search was conducted based on keywords on Google Scholar in order to find literature related to an MME/MMI approach in scientific fields in general. In order to see if any of these articles have been cited by authors related to research in the drinking water sector. With these two searches combined, the search methodology is aimed to yield an exhaustive overview of results related to the keywords. If the implementation of that search methodology does not yield results regarding literature on an MME/MMI approach, then it is plausible that the practice of MME/MMI has not materialised yet within the DWI. On Scopus, the article title, abstract and keywords were sought for the search terms. The results are displayed in Table C.2 in Appendix C. Scopus only contains the abstract of articles (from Elsevier and other parties) and not the full text of an article. All results were scanned for MME/MMI, but none were found to be of relevance to the topic.

On Science Direct the full text of the article can be searched. However, it is not possible to exclude terms (title, abstract, keywords) from the search. In addition, the search engine breaks down search words. For example, multi-modelling results in a search for the word multi, model and modelling and plurals. Which leads to in a large number of returned results that do not match the intent of the search.

Figure B.3: Drinking water chain

For all search terms related to modelling this resulted in a list of 907 articles due to the fact that it contained the word water from the search term "'drinking water company". These were accessed primarily on title to access whether or not an MME/MMI was applied in the research article. If unclear the abstract was examined. This list of articles was scanned for a relation with MME/MMI, but none were found.

On Web of Science, there is a possibility to exclude search options such as title, abstract, keywords or full text. The results are presented in Table C.4 in Appendix C. Also on Web of Science the articles were scanned for a relation with MME/MMI, but none were found. A second search approach was applied on Google Scholar with the aim to find articles related to the topic in order to see if it was cited by authors who have published on drinking water-related research. In order to narrow the search, the articles were only included if the search term was found to be present in the title or the abstract of the article. The results are presented in Table C.5 in Appendix C. No articles were found that showed the application of an MME/MMI for the DWI.

The search for literature for the application of an MME with an MMI has not resulted in any documented peer-reviewed attempts at exploring the potential and suitability of MME for answering research questions in the field of drinking water research. So, it can be concluded there is a knowledge gap on the topic of modelling research questions with an MME approach for the field of drinking water research.

C

Literature Review search terms

Table C.1 shows the search terms related to modelling, the DWI and the logical expression that were used for searches on Scopus, Science Direct and Web of Science. Due to the fact that these three search engines use different search algorithms, the implementation of literature search per search engine differed. Tables C.2 to C.5 show the results from Scopus, Science Direct, Web of Science and Google Scholar.

Search terms related to modelling	logical expression	search terms related to the DWI
Multi-modelling Multi-model ecology Multi-model interface Model operability Model integration Modelling AND simulation Modelling AND method Modelling AND techniques Modelling AND framework Modelling AND approach Modelling AND process	AND	Drinking water company, Drinking water companies, DWI, Drinking water sector

Table C.1: Search terms for literature search

Search terms related to modelling	Number of documents found	Number of relevant documents found
Multi-modelling	0	0
Multi-model ecology	1	0
Multi-model interface	0	0
Model operability	0	0
Model integration	0	0
Modelling AND simulation	8	0
Modelling AND method	10	0
Modelling AND techniques	3	0
Modelling AND framework	5	0
Modelling AND approach	2	0
Modelling AND process	12	0

Table C.2: Literature search results on Scopus

Search terms related to modelling	Number of documents found	Number of relevant documents found
Multi-modelling	220	0
Multi-model ecology	0	0
Multi-model interface	0	0
Model operability	1	0
Model integration	407	0
Modelling AND simulation	907	0
Modelling AND method	907	0
Modelling AND techniques	907	0
Modelling AND framework	907	0
Modelling AND approach	907	0
Modelling AND process	907	0

Table C.3: Literature search results on Science Direct

Search terms related to modelling	Number of documents found	Number of relevant documents found
Multi-modelling	294	0
Multi-model ecology	0	0
Multi-model interface	0	0
Model operability	1	0
Model integration	4	0
Modelling AND simulation	1	0
Modelling AND method	1	0
Modelling AND techniques	1	0
Modelling AND framework	1	0
Modelling AND approach	1	0
Modelling AND process	1	0

Table C.4: Literature search results on Web of Science

Search terms related to modelling	Number of documents found	Number of relevant documents found
Multi-model ecology	19	0
Multi-model interface	105	0
Model operability	170	0
Model integration	71	0

Table C.5: Literature search results on Google Scholar

D

Modelling Examples

Example 1: Participatory modelling for future sourcing locations Finding new location for the sourcing of raw water is a time-consuming procedure due to: 1. the number of actors involved (provinces, municipalities, land-owners and other parties in the underground) 2. research into the hydrological suitability of a location 3. exclusive use of a surface area as a groundwater protection area and the time required for several permit processes. However, the transition from traditional purification processes to Reverse Osmose (RO) enables an opportunity for Oasen, to switch to small-scale decentralized units that can purify types of raw water sources that were considered ill-suitable for traditional purification processes. These need to be located near suitable sources and these have to be identified, designed, permitted and developed, A participatory modelling process with an MME/MMI approach could be beneficial due to the number of actors involved and the opportunity to assemble hydrological, hydraulic, land-use and future water demand models in an multi-model ecology combined with an MMI.

Example 2 Participatory modelling for replacement of end-of-life assets The Dutch subsurface is a crowded place. Several owners of network infrastructure use the subsurface to for the placement of their assets. In case of an emergency such a pipe failure asset owners are allowed to open the subsurface in order to make repairs. Due to legislation in the Netherlands streets are only allowed to be laid bare once every 20 years. Currently, there is a practice in by network owners (of electricity, gas and water networks) in the Netherlands to try and coordinate the replacement of end-of-life assets. However, there is no PM approach were actors can learn from each other policies for EoL replacement. A PM MME/MMI -approach could benefit all actors involved and society by implementing the EoL-replacement polices into models that could interface and determine the overall best course of action taking societal welfare into account.

Example 3 PM for the effects on climate change and shared use of spatial and subsurface resources Oasen is just one of many parties that use the surface and subsurface in her catchment area. Due to change in the subsurface due to desiccation settling of the ground, our current understanding can change. In addition, climate change can be of influence due to changing policies or types of subsurface use. An example of this the increased interest in decentralised heat networks or underground heat cold storage. PM with MME/MMI is an excellent approach to gain more understanding of the individual decisions of organisations in response to a changing environment and the effects on the interest of other actors in the subsurface. Examples where a MME/MMI can aid without a participatory modelling approach

Example 4 MME/MMI for modelling the development of future drinking water demand The long-term development of drinking water question is difficult to model since it is related to other developments that can be interrelated such as: demographical, spatial and urban, institutional, behavioural and technological developments. With a MME/MMI-approach domain experts can build one or several validated models on their domain that can be assembled into an ecology to provide insight into the development of future water demand.

Example 5 MME/MMI integrate several single-use models on failure predictions to gain a bet-

ter and deeper understanding of the pipe fail mechanisms. Several single-use prediction models based on heuristics are currently being used by drinking water companies in order to get an understanding of the fail mechanisms that play a role for the subsurface drinking water infrastructure. However, these single-use models often offer a single-use perspective where a multi-perspective is expected to lead to better decision-making. A MMI for Water Resource Management could be applied here in order to prevent the replacement of assets before their end-of-life time.

E

Average Water demand for scenarios

Agent activity	Water use activities during an agent activity	Water use specified (in liters)	frequency	total water use per activity per 15 minutes	duration in 15-minute periods	[1] PR 2025	[6] Dual	[8] Lux	Scenario [1] PR2040 Water use specified (in liters)	Scenario [1] PR2040 total water use per activity per 15 minutes	Scenario [1] PR2040 duration in 15-minute periods	Scenario [6] Dual Water use specified (in liters)	Scenario [6] Dual total water use per activity per 15 minutes	Scenario [6] Dual duration in 15-minute periods	Scenario [8] Lux Water use specified (in liters)	Scenario [8] Lux total water use per activity per 15 minutes	Scenario [8] Lux duration in 15-minute periods
To Sleep	toilet	6	1	0.1875	32	5,275	0	8,85	5,275	0,16	32	0	0	32	8,85	0,28	32
To Wake Up	toilet	6	1	4.2	4	5,275	0	8,85	5,275	15,71	4	0	12,03	4	8,85	20,6	4
	shower	8	0.7			55,4	45,9	71,4	55,4			45,9			71,4		
	bathroom faucet	5	1			2	2	2	2			2			2		
	pers. consumption	0.2	1			0,2	0,2	0,2	0,2			0,2			0,2		
To Reside day	pers. consumption	0.2	3	0.4	32	0,6	0,6	0,6	0,6	0,35	32	0,6	0,02	32	0,6	0,57	32
To Work	toilet	6	2			10,55	0	17,7	10,55			0			17,7		
To School (or daycare)																	
To Study																	
To Recreate																	
To Shop	n.a.	n.a.	n.a.	n.a.	n.a.	0	0	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
To Cook	kitchen faucet	0.8	1	0.25	3	0,8	0,8	0,8	9,825	3,28	3	12,4	4,13	3	3,55	1,18	3
To Eat	pers. consumption	0.2	1	0.05	4	0,2	0,2	0,2	0,2	0,05	4	0,2	0,05	4	0,2	0,05	4
To Use Appliances	Dish washer	13	1 per day	3.25		2,6	1,7	1,7	2,6			1,7			1,7		
	washing machine	54	1 x per 4 days	9		14	0	14,2	14			0			14,2		
To Water the Garden	kitchen faucet	21	1	21	1	15,2	0	23,1	15,2	15,2	1	0	0	1	23,1	23,1	1
To Reside evening	pers. consumption	0.2	1	0.45	24	0,2	0,2	0,2	0,2	0,48	24	0,2	0,26	24	0,2	0,63	24
	toilet	6	1			5,275	0	8,85	5,275			0			8,85		
	bath	112	0.03			4,1	4,1	4,1	4,1			4,1			4,1		
	bathroom faucet	5	.25			2	2	2	2			2			2		
Out of System	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
						123,675	57,7	164,75	132,7			69,3			167,5		

Figure E.1: Overview of water demand end use mapping from scenarios to the ABM model agent activities

F

Literature from Literature Review

No.	Title	Author, Year
1.A.	Development of an integrated generic model for multi-scale assessment of the impacts of agro-ecosystems on major ecosystem services in West Africa.	(Belem & Saqalli, 2017)
1.B	Ten questions concerning modeling of distributed multi-energy systems	(Mavromatidis et al., 2019)
1.C	HUES: A Holistic Urban Energy Simulation Platform for Effective Model Integration	(Bollinger & Evins, 2015b)
1.D	Industrial ecology in integrated assessment models	(Pauliuk et al., 2017)
1.E	On Holistic Urban Energy Modelling and Optimization	(Evins, 2017)
1.F	Complexity in Industrial Ecology Models, Analysis, and Actions.	(Dijkema et al., 2015)
1.G	Thermodynamical Material Networks for Modeling, Planning and Control of Circular Material Flows	(Zocco et al., 2023)
1.H	Facilitating model reuse and integration in an urban energy simulation platform	(Bollinger & Evins, 2015b)
2.A	Envisioning Building-as-Energy-Service in the European context. From a literature review to a conceptual framework.	(Sibilla & Manfren, 2022)
2.B	Energy Modelling and Analytics in the Built Environment, A Review of Their Role for Energy Transitions in the Construction Sector.	(Manfren, Sibilla, et al., 2021)
2.C	Techno-economic analysis and energy modelling as a key enabler for smart energy services and technologies in building.	(Manfren, Nastasi, & Tronchin, 2020)
2.D	Simulation of Large-Scale Models in Modelica: State of the Art and Future Perspectives	(Casella, 2015)
2.E	Open data and energy analytics - An analysis of essential information for energy system planning, design and operation.	(Manfren, Nastasi, & Tronchin, 2020)
2.F	Comprehensive Simulation Meta Model for Transition Planning and Decision Analysis with Sustainable Impact.	(Billeter, 2021)
3.A	An interoperable software ecosystem to store, visualize, and publish water resources systems modelling data.	(Abdallah et al., 2022)
3.B	Consistent Terminology and Reporting Are Needed to Describe Water Quantity Us	(Grubert et al., 2020)

No.	Title	Author, Year
3.C	Integrating field observations and process-based modeling to predict watershed water quality under environmental perturbations.	(Chen et al., 2021)
3.D	Smart Environmental Data Infrastructures: Bridging the Gap between Earth Sciences and Citizens.	(Ríos Viqueira et al., 2020)

Table F.1: Reviewed literature

G

Results from applying the Model Assessment method

#	Organisation	Model name	Type of model	Description of the model	Modelling paradigm or formalism	Resolution	Scale	Scope (chain activity)	Software environment: platform	Software environment: operating system	Software environment: engine	Open source software	Model accessible through an API	model inputs	model outputs
1	Oasen	Water demand prediction	demand forecasting model	model uses predications of the population dynamics in Oasen territory over time and average consumption of drinking water in order to predict de development of drinking water demand	Hybrid modelling using: statistical and numerical methods	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: 2020 - 2050 Spatial: Oasen area	Production Distribution (?)	n.a.	Windows 10 Pro, 64-bit	Microsoft Excel	No	No	population development, water use	Water demand forcast
2	IcaStat	Water demand prediction	demand forecasting model	model uses predications of the population dynamics in Oasen territory over time and average consumption of drinking water in order to predict de development of drinking water demand	Hybrid modelling using: statistical and numerical methods	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: 2020 - 2050 Spatial:	Production Distribution (?)	n.a.	Windows, version unknown	R-Studio	Yes	No	population development, water use	Water demand forcast
3	Bentley (commercial)	OpenFlows WaterGEMS	hydraulic model	Decision-support tool for water distribution networks	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Distribution	n.a.	Windows 10 Pro, 64-bit	EPANET	No	No	yearly water demand	Water pressure at demand nodes?
4	KWR	Well Field Scheduling Optimiser (WFSO)	hydrology modelling	to model the effect of a change in the sourcing on the quality of the drinking water in the clean water celler	Optimisation	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Sourcing Production	n.a.	Windows	Python	No	No	unknow	
5	Fabrikant Membranen	Reverse Osmoses process modelling	operations process modelling	model to predict the percentages of substances that the R.O.-instalaltion is able to remove from the water sourced in relation to the percentage that oasses the membrames of the R.O.-installation	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Production	n.a.	Windows	Unknown	No	No	water quality parameters as input for the R.O.-process	water quality parameters output
6	Fabrikant Membranen	Reverse Osmoses process monotoring tool	operations process modelling	tooling to determine when it is required to perform preventive maintenance to the R.O.-installation	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Production	n.a.	Windows	Microsoft Excel	No	No	Operarional parameters from the RO-installation	Unknown
7	Oasen	unknown	operations process modelling	coupled excel sheets (on SharePoint) for proces control of operations at the production plants	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Production	n.a.	Windows	Microsoft Excel	No	No	Unknown	Unknown
8	Adviesburo Acacia Water	unknown	Hydrology modelling	model to predict the concentration of GenX substance in drinking water based on the concentration present in the river and the traveltime of riverwater in the soil to the well	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Sourcing	n.a.	Unknown	Unknown	Unknown	No	Unknown	Unknown
9	Oasen	AquaView	operations process monitoring (not modelling)	database for water quality data for production proces + ruw water + rein water, alerrting when threshold values for company standards and legal standards are exceeded	n.a.	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Sourcing Production	n.a.	Unknown	Unknown	Unknown	No	Unknown	Unknown
10	Oasen / KWR	Aqua Priori: soil	hydrology modelling	modelling of environmental fate: the behaviour of substances in the soil	Nummerical modelling	Attributes: Behavoir: Entities: Processes: Spatial: Temporal:	Temporal: Spatial:	Sourcing	n.a.	Unknown	Unknown	Unknown	No	Unknown	Unknown

Figure G.1: Model Assessment method applied at Oasen

H

Appendix for Chapter 6

No.	Classification	Stakeholder	Description
1	Advocacy group	Association of Water Companies (VEWIN)	Vewin is the representative of the Dutch drinking water sector
2	Education institution	Universities, HBOs, MBOs	An establishment where people gain an education
3	Government organization	Cities (shareholders of Oasen)	Cities provide the drinking water company a licenses to provide its citizens with drinking water
4	Government organization	Provinces	Provinces provide the drinking water company extraction permits for the sourcing of production water
5	Government organization	Dutch government	the government is responsible for the drinking water supply
6	Government organization	Government permit office	Checking permit applications against the law and regulations
7	Government organization	Supervisor drinking water supply	the Human Environment and Transport Inspectorate (ILT) monitors the public drinking water supply. This concerns the quality of drinking water, the security of supply and the efficiency of the drinking water supply
8	Government organization	City sewer department	A party with an underground network infrastructure in the subsurface
9	Government organization	Rijkswaterstaat	the executive agency of the Ministry of Infrastructure and Water Management in the Netherlands. It manages and develops the main roads, main waterways and main water systems on behalf of the ministry.
10	Government organization	Waterboards	the regional governing body solely charged with the management of surface water in the environment
11	Knowledge institution	Research institutions	An establishment founded for doing research for clients
12	Network company	Cable company	A party with an underground network infrastructure in the subsurface
13	Network company	Distributed heat company	A party with an underground network infrastructure in the subsurface

No.	Classification	Stakeholder	Description
14	Network company	Drinking water companies	Drinking water companies that deliver drinking water to their customers in their geographically assigned area
15	Network company	Electricity company	A party with an underground network infrastructure in the subsurface
16	Network company	Gas company	A party with an underground network infrastructure in the subsurface
17	Network company	Glasfiber company	A party with an underground network infrastructure in the subsurface
18	Network company	Oasen drinkwater	A party with an underground network infrastructure in the subsurface
19	Network company	Telephone / Cable company	A party with an underground network infrastructure in the subsurface
20	Private company	Accountant firm	the accountant firm manages the financial records of Oasen and ensure the compliance with tax laws and regulations
21	Private company	Certification authorities	Company that officially declares that a product, process or service meets a standard
22	Commercial company	Contractor Well drilling	Supplier of services
23	Commercial company	Consultancy companies	Supplier of knowledge
24	Commercial company	Software supplier	Supplier of software
25	Commercial company	Supplier distribution network sensors	Supplier of hardware for DWDS
26	Commercial company	Supplier electronic water meters	Supplier of hardware for DWDS
27	Commercial company	Supplier process chemicals	Supplier for operational processes
28	Commercial company	Supplier R.O. installation	Supplier for operational processes
29	Professional Experts	Expert committees	Supplier of knowledge

Table H.1: Stakeholder description

No.	Stakeholder	Interest	Role
1	Association of Water Companies (VEWIN)	Coordination of research endeavours	Indirect
2	Universities, HBOs, MBOs	Coordination of research endeavours	Direct
3	Cities (shareholders of Oasen)	Establish ground water protection areas	Indirect
4	Provinces	Monitor the depletion of water for sourcing	Indirect
5	Dutch government	Responsible for the drinking water supply	Indirect
6	Government permit office	Grants building permits	
7	Supervisor drinking water supply	Supervises the operation of Oasen	Indirect
8	City sewer department	Coordination of activities in the subsurface	Indirect
9	Rijkswaterstaat	Responsible for waterways	Indirect
10	Waterboards	Responsible for public water bodies	Indirect
11	Research institutions	Coordination of research endeavours	Direct

No.	Stakeholder	Interest	Role
12	Cable company	Coordination of activities in the subsurface	Direct
13	Distributed heat company	Coordination of activities in the subsurface	Direct
14	Drinking water companies	Coordination of research endeavours	Direct
15	Electricity company	Coordination of activities in the subsurface	Direct
16	Gas company	Coordination of activities in the subsurface	Direct
17	Glasfiber company	Coordination of activities in the subsurface	Direct
18	Oasen drinkwater	Coordination of activities in the subsurface	Direct
19	Telephone / Cable company	Coordination of activities in the subsurface	Direct
20	Accountant firm	Responsible for financial reporting	Indirect
21	Certification authorities	Responsible for required certificates for Licence to Operate of Oasen	Indirect
22	Contrator Well drilling	Commercial interest	Indirect
23	Consultancy companies	Commercial interest	Indirect
24	Software supplier	Commercial interest	Indirect
25	Supplier distribution network sensors	Commercial interest	Indirect
26	Supplier electronic water meters	Commercial interest	Indirect
27	Supplier process chemicals	Commercial interest	Indirect
28	Supplier R.O. installation	Commercial interest	Indirect
29	Expert committees	Providing advice on applying regulations in a company-specific case	Indirect

Table H.2: Stakeholder interest

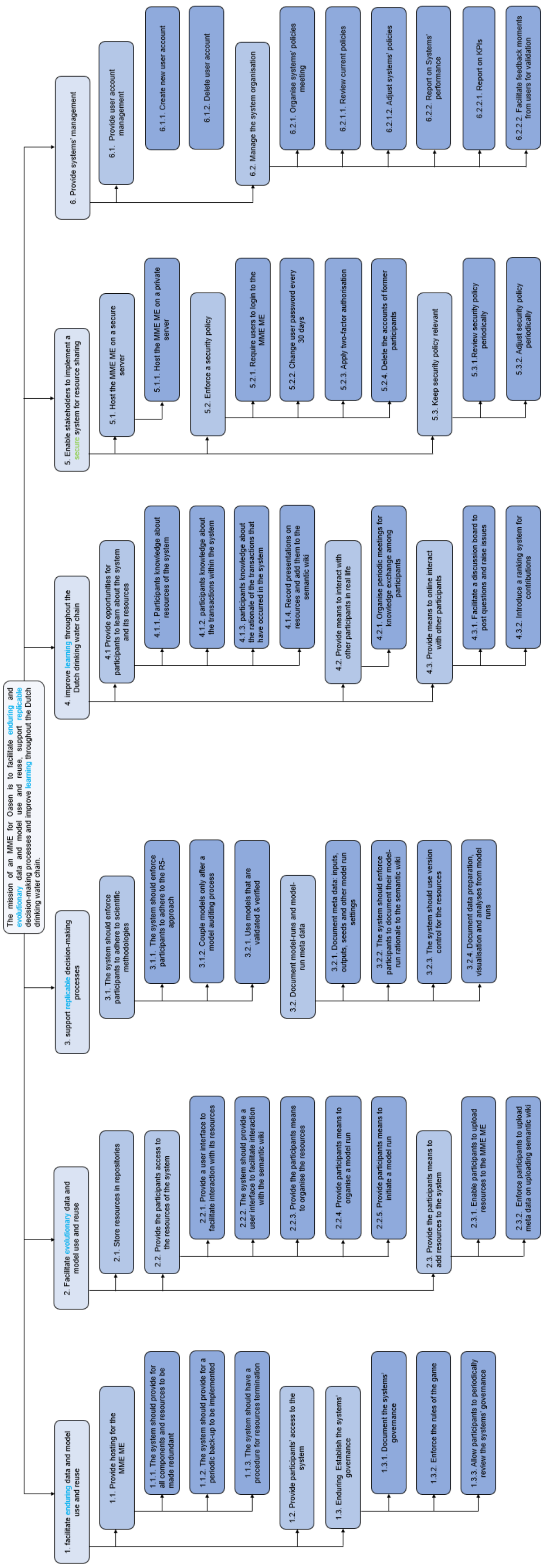


Figure H.1: MME+I System Requirements Structure

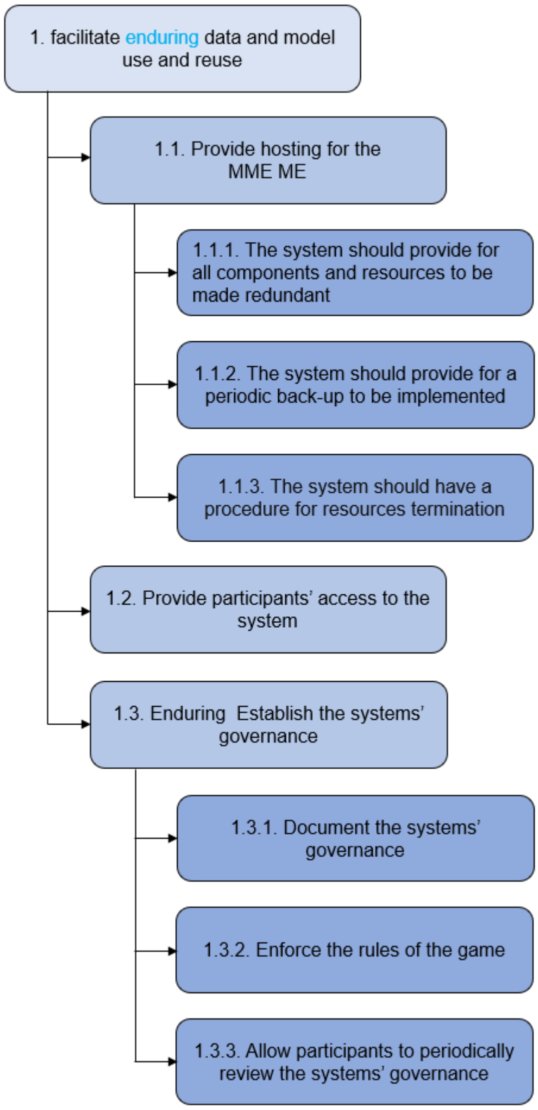


Figure H.2: MME+I System Requirements Structure branch 1 of 6

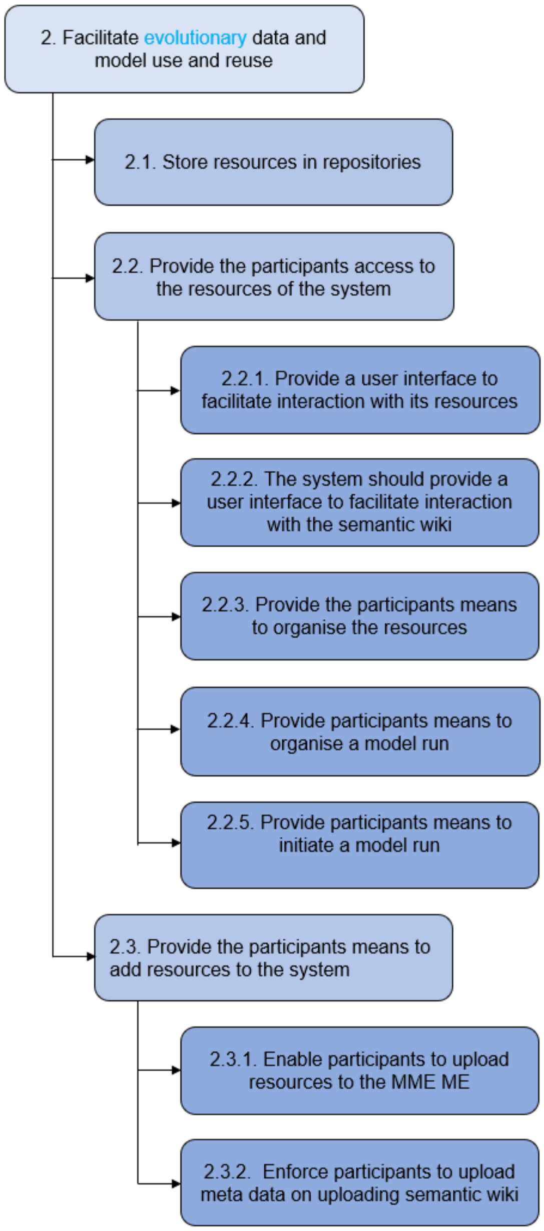


Figure H.3: MME+I System Requirements Structure branch 2 of 6

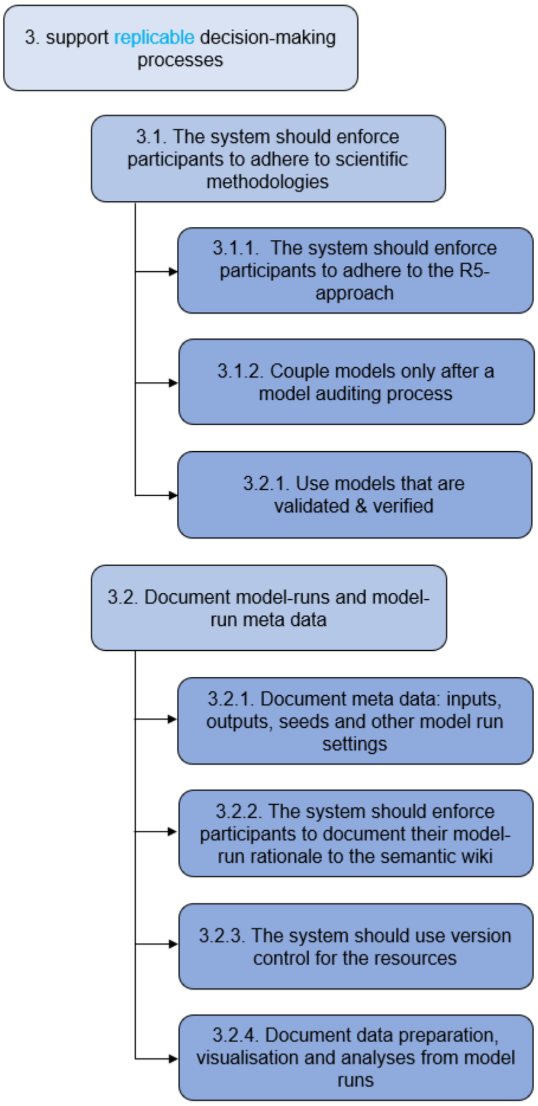


Figure H.4: MME+I System Requirements Structure branch 3 of 6

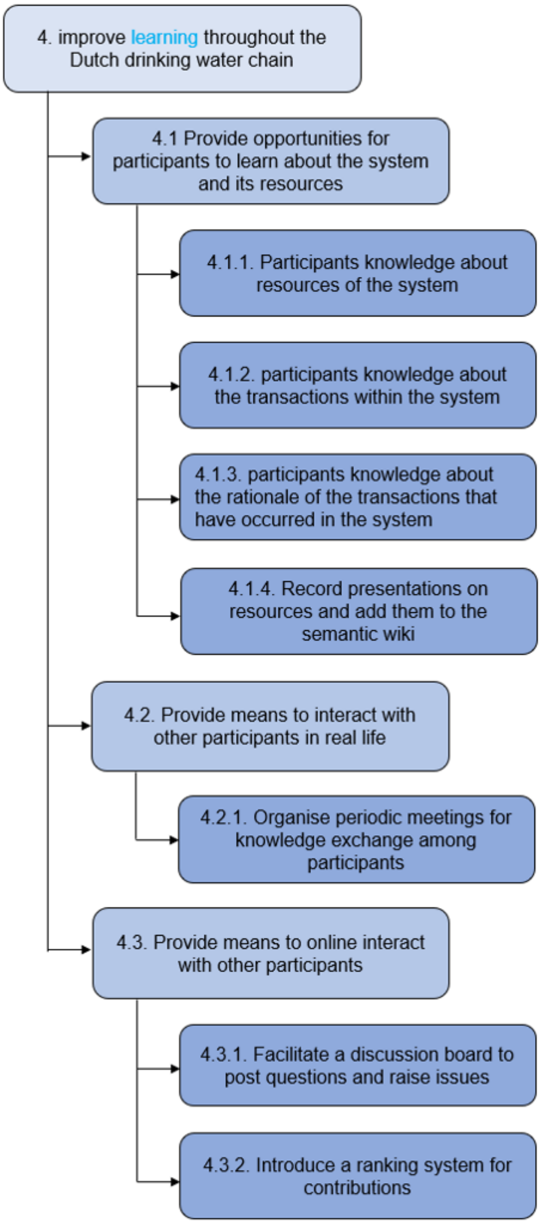


Figure H.5: MME+I System Requirements Structure branch 4 of 6

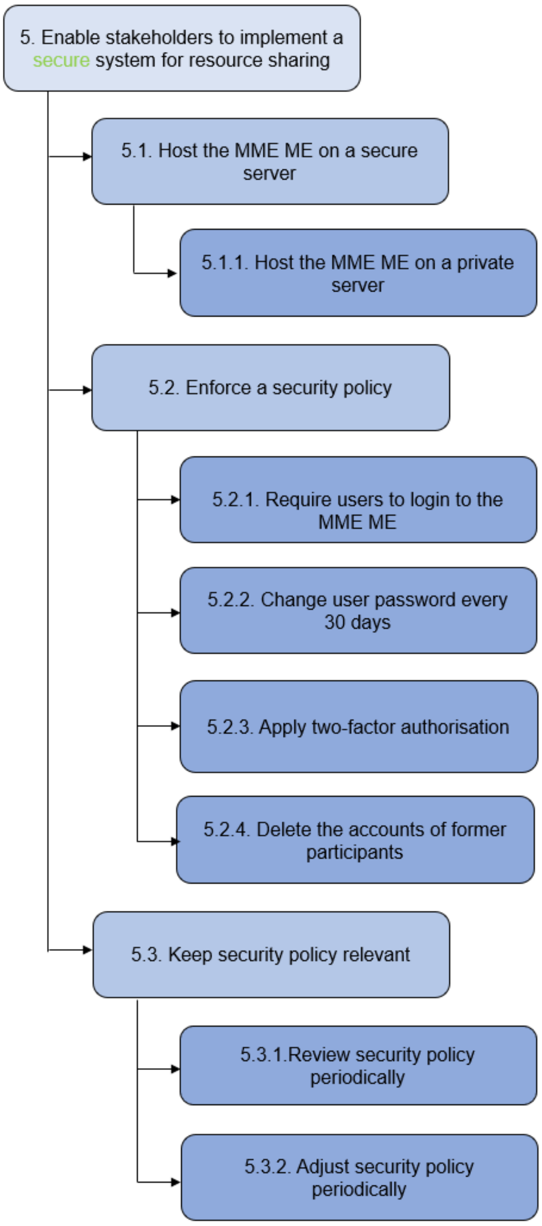


Figure H.6: MME+I System Requirements Structure branch 5 of 6

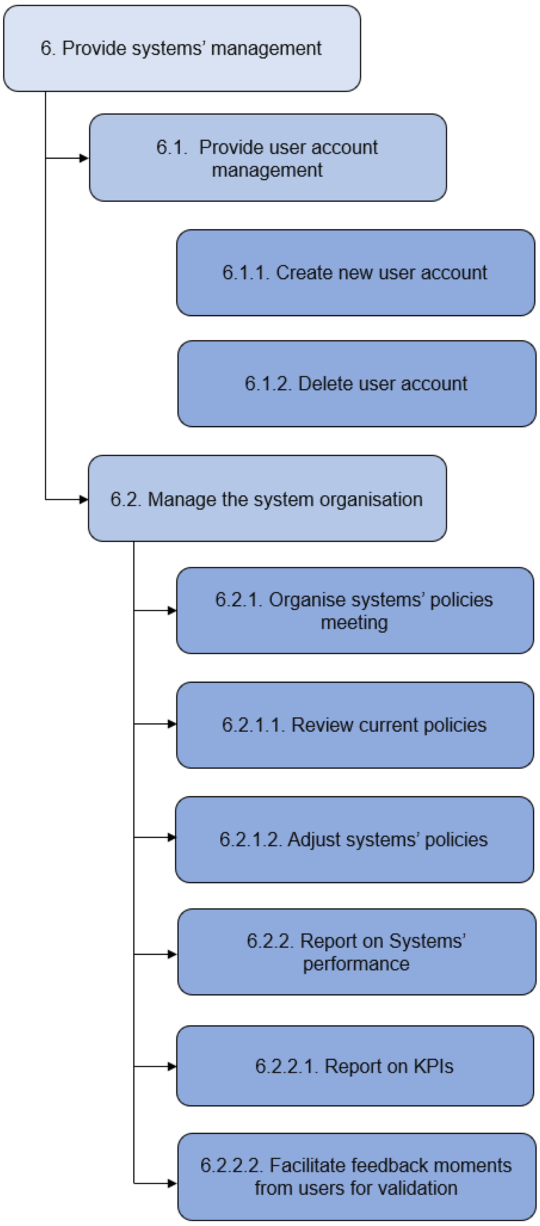
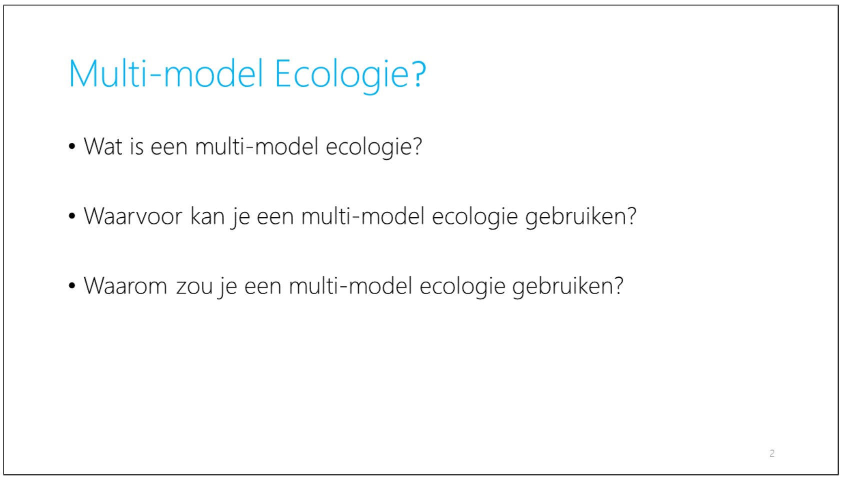


Figure H.7: MME+I System Requirements Structure branch 6 of 6

I

Presentation: Designing an MME for Oasen

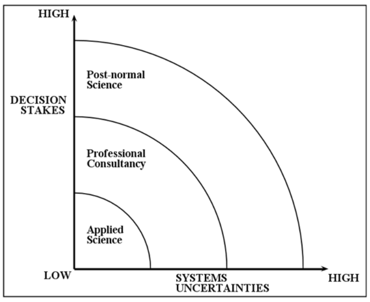


Concepten

1. Post-normal science
2. Gecompliceerd vs. complex
3. Modelleren en computersimulatie
4. Top-down vs. bottom-up
5. Projecten vs. processen
6. Single-use modellen vs. model re-use
7. Multi-Model Ecologie
8. Multi-Model Interface
9. Participatory Systems
10. Participatory Modelling

3

C1: Post-normal science



FrancoisDM - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16042041

4

C2: Gecompliceerd vs. Complex

" ... the main difference between *complicated* and *complex* systems is that with the former, one can usually predict outcomes by knowing the starting conditions.

In a complex system, the same starting conditions can produce different outcomes, depending on interactions of the elements in the system."

gecompliceerd

complex

Sargut & McGrath, Harvard Business Review

5

C3: Modelleren en computersimulatie

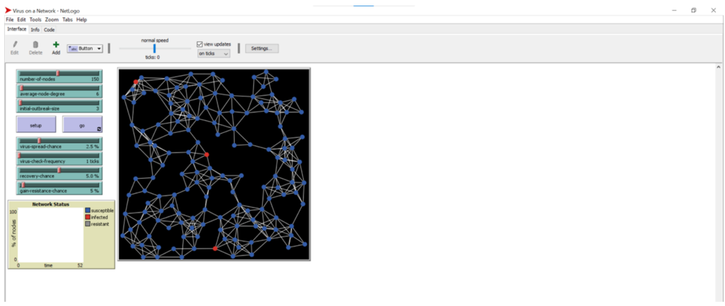
Wat is een model?
Een model is een representatie van een systeem bedoeld om een antwoord te geven op een vraag over dat systeem.

Waarom maken wij gebruik van modellen?
Omdat iets uitte proberen in de werkelijkheid vaak niet kan.

Wat is een (computer-)simulatiemodel?
Een simulatiemodel is een model dat de werking van een systeem kan imiteren over de tijd heen.

6

C3: Modelleren en computersimulatie



7

C4: Top-down vs. bottom-up aansturing

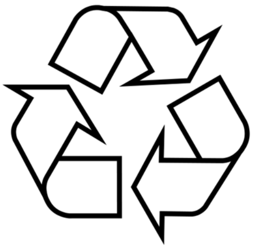
hierarchie vs. zelf-organisatie

8

C4: Projecten vs. processen

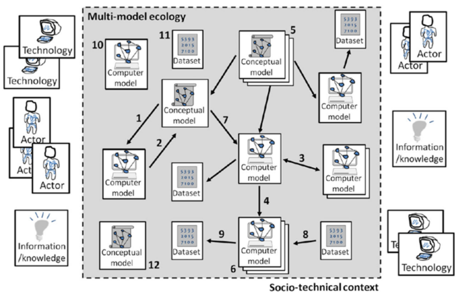
9

C6: Single use modellen vs. model re-use



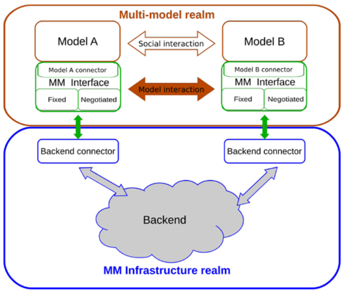
10

C7: Multi Model Ecologie



Nikolic, I., Warnier, M., Kwakkel, J. H., Chappin, E. J. L., Lukszo, Z., Brazier, F. M., ... & Palensky, P. (2019). Principles, challenges and guidelines for a multi-model ecology. 11

C8: Multi-model Interface



Nikolic, I., Warnier, M., Kwakkel, J. H., Chappin, E. J. L., Lukszo, Z., Brazier, F. M., ... & Palensky, P. (2019). Principles, challenges and guidelines for a multi-model ecology.

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C9: Participatory Systems

Participatory systems are large-scale social-technical systems enabled by

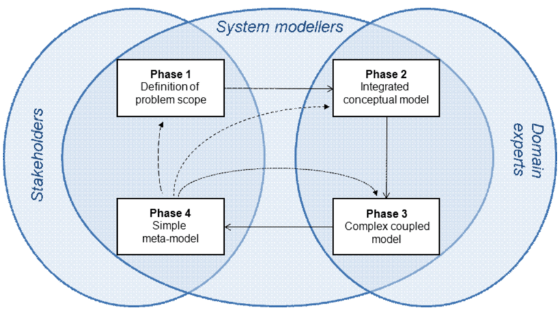
- technology/connectivity,
- coordinating
- and orchestrating self-organization

designed to provide individuals and organisations with the ability to act and take responsibility in today's networked society.

www.participatorysystems.nl/

13

C10: Participatory Modelling



14

Main research question

How can a multi-model ecology aid the design of a futureproof drinking water distribution system?

15

Sub research-questions

1. Which modelling methodologies or modelling techniques are applied in the field of Water Resource Management?
2. What are the design principles and typical characteristics of operational MME's for peer-reviewed research?
3. What are the design specifications for a MME for the DWI?
4. What lessons can be learned from the an iterative Systems Design approach for the design of an MME?

16

Multi-model ecologie?

- Wat is een multi-model ecologie?
- Waarvoor kan je een multi-model ecologie gebruiken?
- Waarom zou je een multi-model ecologie gebruiken?

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