Exploring interoperability of computation models and digital twins

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Version v1.0
Status Final version
Date 10 juni 2025

Contents

Thank you

We would like to express our thanks to all the experts interviewed for their valuable contributions to the creation of the report ‘Research for interoperability of computation models and digital twins’. Their insights and expertise have played a crucial role in the findings and recommendations on the interoperability of computation models in digital twins. The shared experiences and perspectives have enabled us to paint a nuanced and comprehensive picture of the current state of affairs, ideas and possibilities surrounding the interoperability of computation models. Without their willingness to share time and knowledge, this exploration would not have the depth and relevance it now possesses. We hope that our joint efforts will contribute to further development and cooperation on the use of computation models in digital twins.

In addition, we thank Dutch Metropolitan Innovations (DMI) for facilitating this exploration. The DMI ecosystem provides the domains of sustainable, smart cities with new tools from the digital world, which enabled us to carry out this exploration. Our appreciation also goes to the Ministry of Housing and Spatial Planning (VRO) for their support from the Digital Twins and View of Flevoland program. Finally, we would like to thank the colleagues at Geonovum, who have provided critical additions and improvements from the ‘Digital Twin as a Service’ perspective.

The cooperation and support of all stakeholders has significantly enhanced the quality and depth of this report.

Michel Grothe and Eric Koomen

Management summary

As digital representations of the physical environment, digital twins play an important role in supporting decision-making in various areas such as mobility, housing, and climate adaptation. The aim of this exploration is to understand how computation models, which are essential for the functioning of digital twins, can work together and how they can be shared in a way that contributes to efficiency, saving time and costs, and increasing the public value of digital twins. This 'Explore interoperability of computation models and digital twins' focuses on exploring the possibility of integrating computation models into digital twins in a modular, service-oriented and interoperable way.

The exploration was carried out as part of the Dutch Metropolitan Innovations (DMI) program, an innovation initiative that focuses on developing a digital ecosystem for sustainable, smart cities as a collaboration between governments, companies, and knowledge institutions. This study looked at the interoperability of computation models in digital twins from a legal, organizational, semantic and technical perspective. In addition, the report makes recommendations for a further contribution to the interoperability of computation models within the context of digital twins that are applied in the physical environment.

The findings in this report are based on a combination of interviews with 20 Dutch experts from the field of computation models and digital twins, on desk research and an expert workshop. The results provide insight into best practices, developments, innovations and challenges surrounding the integration of computation models in digital twins. The exploration points out that the interoperability of computation models in digital twins is of great importance for the realization of applications that require more complex or integral considerations, such as those that come together in the ambitions around sustainable cities. This can be achieved by developing collaboration, agreements and standardization and modular digital twins, which facilitate the sharing and reuse of computation models and computational infrastructure. The collaboration between the many different parties involved and the creation of an open infrastructure for computation models are also key to the success of using digital twins to support policy, planning and decision-making on complex issues in the physical environment.

The main findings of the reconnaissance are:

1. To increase the effectiveness of digital twins, computation models must be interchangeable and able to work well together. This can only be achieved by using standardized interfaces and protocols covering all aspects of interoperability, legal, organizational, semantic and technical as well as operational aspects. Interoperability is essential for the success of digital twins;
2. Standardization is important to make models work better together, but it does not mean striving for universal models that can be used for a wide range of applications.
3. Collaboration and knowledge sharing is crucial for the successful integration of computation models into digital twins. This requires close cooperation between governments, knowledge institutions and the private sector. Agreements must be made, for example, on quality assurance and the use of computation models and on revenue models. In addition, there is a need for a national strategy and an organizational infrastructure;
4. Computation models are not always used for what they are intended and are not always validated before they are used. Quality frameworks and audits are needed to ensure reliability. There is a need for quality frameworks to determine when a model is suitable for a particular use. This requires a clear view of fit-for-purpose and quality and reliability in relation to the intended application (validation and certification).
5. The Handbook of Good Modelling Practice provides guidelines for transparency, reproducibility and validation, which increases the acceptance of model results. It is

recommended to introduce a quality framework, explore a model register, draft licensing conditions and carry out audits. These measures shall promote transparency, re-use and scientific progress of computation models;

6. Open communication on modelling, quality aspects and application domain can contribute to wider acceptance of model-based outcomes among policy makers, citizens and other stakeholders. Complexity is at odds with transparency and insight into correct applications. The ideal model is as complex as necessary and as simple as possible.
7. In contrast to geodata, for which standardized guidelines and guidelines now exist, uniform agreements have not yet been made for the accessibility of computation models in digital twins. This is understandable given the much more complex nature of models, but limits the possibilities for coupling and reuse. There are now some applications and testbeds in which standards for computation models are applied, such as the Basic Modelling Interface and OGC API Processes. These can help connect different computation models and facilitate data exchange with and between computation models. This is an important challenge that needs to be addressed in order to further develop digital twins in the Netherlands and increase their impact;
8. Promoting modular and reusable design principles makes it possible to flexibly integrate and reuse computation models within different digital twins. This promotes the scalability and reuse of existing computation models and helps reduce costs and time commitment for the development and implementation of new applications. The reference architecture NLDT, which is currently being developed, gives a first impulse for its implementation in practice;
9. High-performance computing is increasingly used in digital twins, with GPUs and multi-threaded computing accelerating complex simulations. AI algorithms are used for simulations, model validation and optimizing existing models. For an effective implementation, it is recommended to pay attention to workflow management, AI applications and collaboration with the Digilab Applied Knowledge.
10. Close collaboration between governments, research institutes and private companies is essential for creating a digital ecosystem in which computation models can be effectively shared and reused. Strengthening cooperation between stakeholders when using computation models and digital twins is also recommended. DMI and the national program Digital Twins from View of the Netherlands give a first start as an important collaboration for the realization of interoperability and the shared infrastructure between different digital twins. This could pave the way for a wider use of digital twins.

List of abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
AR/VR/XR	Augmented Reality/Virtual Reality/eXtended Reality
BAG	Key registration Addresses and Buildings
BMI	Basic Modelling Interface
GRT	Key registration Topography
BRO	Key registration Subsurface
CBS	Central Bureau of Statistics
CPT	Capabilities Periodic Table
DT	Digital Twin
DMI	Dutch Metropolitan Innovations
DSS	Decision Support System
DTaaS	Digital Twins as a Service
DTC	Digital Twin Consortium
DTE	Digital Twin Engine
EIF	European Interoperability Framework
EU	European Union
FAIR	Findable, Accessible, Interoperable, Reusable
GBP	Green Benefit Planner
GIS	Geographic Information System
GPU	Graphics Processing Unit
HTTP	Hypertext Transfer Protocol
IenW	(Ministry of) Infrastructure and Water Management
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
JSON	JavaScript Object Notation
KNMI	Royal Netherlands Meteorological Institute
MCA	Multi-Criteria Analysis
MKBA	Societal Cost Benefit Analysis
NHI	Dutch Hydrological Instruments

NMDC	National Model and Data Centre
NRM	Dutch Regional Model
NWM	National Water Model
LCA	Life cycle analysis
LMS	National Model System
DTP	Open Digital Twin Platform
OGC	Open Geospatial Consortium
OMF	Open Modeling Foundation
OpenMI	Open Modelling Interface
REST	Representational State Transfer
RIVM	National Institute for Public Health and the Environment
STOWA	Foundation for Applied Research on Water Management
TNO	Netherlands Organization for Applied Scientific Research
TO	Applied Research Institute
UX	User Experience
VRO	(Ministry of) Housing and Spatial Planning
VU	Vrije Universiteit Amsterdam (University in Amsterdam)
WPS	Web Processing Service
WOZ	Key registration Valuation of Real Estate
WUR	Wageningen University & Research
XML	eXtensible Markup Language

1. Introduction

1.1 Introduction

The space in our country is becoming increasingly scarce and we want a lot together on a small piece of earth. To solve this puzzle, it is necessary to approach the various spatial tasks from different angles. This requires a common information base. Digital representations of the physical environment or digital twins help to make the available data about the physical environment visible to all involved. Computation models ensure that these data can also be brought to life, for example in simulations. This allows a conversation to take place about desired and undesirable (additional) effects of interventions in the physical environment. In the Netherlands, therefore, we are now working on a national network of local digital twins that should make it possible to use each other's data, computation models and visualizations to solve our societal tasks (Ministry of VRO, 2025a).

The basic idea of the intended network of digital twins is that the components (data, models, visualizations) they consist of are shared or connected because this leads to more efficiency, shared insights, time savings and lower costs. These interconnections can consist of sharing data between building blocks of a digital twin, between different digital twins, or with external data platforms and computation models. There are several ways to connect digital twins, for example by providing access to sensor data and data APIs and visualizations, or by recording and executing different computation models. Connections to computation models can make sense to record results, which are relevant for policy analysis, scenario planning and making operational, tactical and strategic decisions. Various standards are available for access to data (and metadata), such as for capturing semantics, exchange formats and various types of APIs.

For connecting digital twins, it is important that they can be assembled in a modular, service-oriented and interoperable way. Open standards play an essential role in this. In the Dutch situation, various experiences have been gained over the past ten years with making various static and dynamic geodata sources interoperable and successful implementations are now available. The agreements for this are often laid down in guidelines. Such standardization agreements are not yet in place for computation models (Raes, 2025). How can computation models – the heart of the function of digital twins – be approached and shared to increase the utility and public value of digital twins? In other words, how can computation models be offered modular, service-oriented and interoperable for reuse in digital twins? These are the questions with which we started this exploration.

1.2 This exploration

The aim of this exploration is to get a better picture of how computation models can be connected to digital twins so that the interaction with computation models can be set up in a modular, service-oriented and interoperable manner. To this end, we want to catch up on the current state of affairs regarding the use of computation models in digital twins and the application of open interface standards for computation models and computation models interoperability in the Netherlands. We thus make an inventory of which open interface standards are available and used in the Netherlands and for which computation models and applications. And that from the perspective of digital twins applications in the physical living environment.

The presentation of experiences and knowledge in the Netherlands about a uniform and standardized access to computation models is the subject of this study. This takes into account the complexity of the work field of the computation models. There are many different types of computation models, with different goals and functions and in different application domains. The implementations of computation models are also varied and diverse. This complexity and diversity means that an exploration of a possible solution or solutions for a uniform accessibility of the computation models in digital twins starts with exploring the experiences gained with computation models and interoperability in the Dutch field of work. Various international initiatives already exist, which work on uniform and standardized access to computation models, for example OpenMI, Basic Modelling Interface, OGC API Processes, which may also be relevant for the Netherlands.

This exploration certainly did not intend to be complete. Findings and recommendations are the result of a large number of interviews with Dutch experts and (source) information provided by them. The aim of the exploration is also to focus on relevant areas and topics to be explored when it comes to interoperability of computation models in the context of the use of digital twins for the physical environment. Here we focus specifically on the physical environment and exclude digital representations of, for example, organisms or people (such as in medical applications), production processes (from industry) or more social applications (e.g. interaction between groups in society).

1.3 Dutch Metropolitan Innovations

This exploration was carried out as part of the Dutch Metropolitan Innovations (DMI) program. This program focuses on developing a digital ecosystem that facilitates data exchange between governments and companies in the mobility and urbanization sectors. The goal is to make data findable, usable and interchangeable, which contributes to smart and sustainable urban solutions. DMI is a National Growth Fund[1] initiative led by the Ministry of Infrastructure and Water Management (IenW), in collaboration with the Ministry of the Interior and Kingdom Relations, various municipalities, provinces, knowledge institutions and private partners. The main objectives of the program are:

- Creating a uniform technical and organizational infrastructure for data exchange, including clear agreements on data use, privacy and security;
- Encouraging cooperation between governments and industry to develop innovative solutions to sustainability challenges in urban areas.

The program runs from 2023 to 2027 and aims to make significant progress in achieving smart and sustainable urban environments over this period. The National Growth Fund has invested €85 million in strengthening the DMI ecosystem, with additional contributions from the business community (€42 million) and relevant governments (€50 million). The aim of DMI is to improve the physical environment by using digital innovations such as digital twins. As a result, cities need to become more sustainable, livable and connected. An important aspect of this collaboration is the sharing of knowledge and the development of best practices in the field of digital twins, standards and interoperability. Interoperability between the different digital twins is the basis of Digital Twins as a Service (DTaaS).[2] This development project aims to develop a national geo-information infrastructure, which makes it possible to share and use not only data, but also computation models and visualizations. To this end, DTaaS shall carry out the following activities in the period 2024-2027:

- Promoting use case, knowledge and organizational development to facilitate and optimize the use of digital twins;
- Developing a national reference architecture with standards and agreements to facilitate interoperability and reuse of components within digital twins;
- Conducting explorations, research, guidelines and testbeds to test and refine concepts and standards in practice in close collaboration with the province of Flevoland and

[1] See https://www.nationaalgroeifonds.nl/overview-on-going-projects/theme-mobility/digital-ecosystem-mobility-and-smart-city?

[2] See https://www.geonovum.nl/themes/digital-twins

municipalities such as Almere, Dronten and Lelystad (within the fieldlab 'Zicht op Flevoland'[3]).

DTaaS strives for a national ecosystem of modular building blocks with which digital twins can be easily created, deployed and reused. The aim of this project is the development of agreements, standards and best practices, so that digital twins can be assembled modularly, service-oriented and interoperable. This exploration of computation models and interoperability was conducted from DMI and DTaaS.

1.4 Approach

The exploration focuses on identifying and discussing interoperability and best practices to integrate computation models into digital twins in a modular, service-oriented and interoperable way. This includes discussing existing approaches, standards and practices in the Netherlands and the application within digital twins. The approach includes a combination of expert interviews, desk research and workshops:

1. Expert interviews with professionals in the field to gain insight into how computation models are currently linked to digital twins and what can be improved;
2. Desk research and analysis of submitted documents and reference architectures, ongoing digital twin projects and initiatives such as OpenMI, Basic Modelling Interface, and OGC API Processes;
3. Discussing results and next steps with experts and stakeholders (workshop and discussions).

The research does not focus on testing an interface standard or setting up a test bed, but is limited to exploration and discussion with findings and recommendations. The approach aims to provide insights for next steps, which further contribute to the interoperability of computation models within digital twins in the Netherlands.

For this exploration, several Dutch experts working with computation models and digital twins discussed aspects of interoperability of computation models. Appendix 1 gives an overview of the consulted experts and the questionnaire we used as a basis. During the interviews, not only the technical aspects were discussed, but also the organizational challenges of model links. The focus of the discussions was always on whether open standards could be helpful in connecting different computation models in digital twins and various applications.

1.5 Reading guide

This guide helps you navigate through the document in a targeted way. Chapter 2 discusses how digital twins are used in the physical environment and what their build-up and maturity stages are. Interesting for readers who want to understand how digital twins work and how they evolve in terms of functionality. Chapter 3 provides insight into different types of computation models for the physical living environment, including an overview of the modelling cycle and different classifications of models by function, approach and application domain. This illustrates the diversity of computation models and their role in digital twins for policy, planning and decision-making.

Chapter 4 details the interoperability of computation models for digital twins, addressing legal, organizational, semantic, technical dimensions of interoperability. Specific topics include open standards, modular architecture, workflow management and (in limited detail) technology. In addition, we pay attention to some aspects of use that contribute to the responsible use of models. This chapter is intended for experts and policy makers, who develop and use digital twins and who

[3] See https://www.zichtopnl.nl/digitaltwins/fieldlabs/zicht+op+flevoland

want to focus on improving the collaboration and interoperability of computation models in digital twins.

Chapter 5 summarizes the main findings and practical recommendations. This is suitable for decision-makers and stakeholders, who are looking for the conclusions and recommendations for follow-up actions. Finally, an overview of the literature consulted (reference list) and the experts interviewed who contributed to the exploration is attached. Useful for researchers and other interested parties who are looking for further details and substantiation.

2. Digital twins

2.1 Digital twins for the physical environment

In this introduction, the concept of digital twins is[4] explained by reflecting on some examples of digital twins and some definitions. There are different images about digital twins. For one, a digital twin is a 3D design of a building or home in a construction project, another thinks of real-time information from the sensors in a bridge to predict the maintenance cycle of the bridge. And for yet another, the digital twin performs a simulation of a flood after a dike breach or predicts what our land use will look like in 2050. Digital twins are used for many different purposes in the Netherlands (Van Apeldoorn et al., 2023). Below we describe some recent applications.

2.1.1 Application example 1 - Maintenance bridge

The idea of digital twins is actually decades old. We have been developing, simulating and testing machines and other objects with 3D software for years, so that they do what they are made for when they go into production. But then a machine also needs to be maintained. Although maintenance is registered by suppliers and users, it often lacks a clear picture of all the maintenance and spare parts of a machine.

Take for example a bridge (see Figure 1). Such an object consists of various components such as the concrete structure, the road surface, the suspension, railings, etc., which are supplied and maintained by various parties. For maintenance we want to know exactly which parts the bridge consists of and when these parts need to be replaced (Adriaanse, n.d.). For this purpose, we collect data about the maintenance carried out per part, the suppliers, the replacement material, but above all also data about the part itself, such as wear and tear, defects and age. The data is collected through inspections and increasingly inspections are carried out continuously with the help of sensors. With a digital twin, you first make this clear. You visualize a bridge in a digital environment and can zoom in per component and see exactly what the maintenance status is (Adriaanse, n.d.). This opens up opportunities for more efficient management and maintenance.

In practice, maintenance is often preventive in nature. A part is replaced or repaired after a certain, prescribed period of time, often because the service life of the part is predetermined (often by the supplier). This can mean that a part is replaced that could have lasted for years, but it also happens that a part breaks prematurely with all the consequences that this entails. A digital twin can be used not only for preventive maintenance, but also for recognizing future problem situations, a predictive twin[5]. Thanks to (historical) data from sensors and new data analysis techniques, such as predictive analytics and machine learning, it is possible to recognize patterns and make predictions about maintenance and replacement of the parts. With the help of some predictive models, it is also possible to simulate situations. What happens to a bridge as soon as freight traffic increases or heavier electric cars continuously cross the bridge? Which parts are under the most pressure? The new insights ensure that parts are repaired or replaced on time and service sessions are planned and executed smarter. And with the use of sensors and real-time data, predicting the status of the bridge is no longer static activity, but a continuous process of data processing. The digital twins also provide the visual presentation of the insights into the maintenance process.

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[4] The term ‘digital twin’ is also often used in the Netherlands, but we prefer the Dutch term.

[5] See https://www.tno.nl/nl/newsroom/insights/2024/12/make-infrastructure-smarter-more sustainable/

Figure 1 - A bridge and its digital twins (source: freely based on TNO).

2.1.2 Application example 2 – Construction of Brainport Smart district residential area

We have a big challenge with the housing challenge in the Netherlands and the construction of about one million new homes. Where these homes should be located is an important political issue. The government, provinces and municipalities use 3D simulations and digital twins for the spatial building assignments with the developers and future residents. The digital twins help in the search for considerations for an optimal area-oriented environmental quality, which must ensure a healthy, safe and attractive living environment for future residents. During the planning process in a digital twin, the environmental quality and sustainability in an area is inventoried and visualized. Through adjustments, the plan can be optimized. The environmental quality is displayed via indicators with report figures.

From the moment of construction of a new residential area, the digital twins can be used to show home seekers what the future district or street will look like (see Figure 2), as[6] was done for Brainport Smart District in Helmond. By paying a virtual visit, you can see exactly what the new neighborhood will look like and really experience and understand the neighborhood. With the help of smart 3D models, based on all kinds of data, you get a realistic insight into the impact of future plans. Residents can also configure their homes in digital twins. The digital twins then immediately show how your future home relates to the intended quality of the living environment. Do you prefer a flat roof, a dormer window or an extension? Or do you want to install solar panels immediately and see what the yields are? If your wishes do not fit within the set rules, the digital twins provide insight into adjustments that you can make to stay within the applicable rules. This is possible if the urban vision, quality requirements, building and environmental rules and computation models are incorporated into the digital twin. As a future resident, you can experience the neighborhood before you start living there. This gives you insight into the building possibilities on the plot and you can see which facilities are available in the neighborhood. Or you can use the digital twins to gain insight into environmental aspects such as noise and air quality in the district.

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[6] See https://brainportsmartdistrict.nl/project/de-digital-twin-van-geodan/

Figure 2 - Design of the Brainport Smart District residential area in Helmond (source: freely based on Geodan).

2.1.3 Application example 3 - Simulation of flooding

Partly due to climate change, our summers are getting warmer and drier. The climate-adaptive design of the physical environment is not just about heat stress and drought. Also rain showers become shorter and more intense. Due to this heavy rainfall, streets are flooded and flooding is becoming more common. A digital twin visually shows where potential flood-prone locations are. By linking a sewage model (how much water can it process?) to the ground level model (with altitude data used for simulation of flowing of water), extreme rainfall can be simulated in a digital twin. Such a simulation provides insight into the amount of water on the street after a heavy shower and where that water comes from. Municipalities and citizens see the possible consequences of extreme precipitation and can prepare themselves and possibly take preventive measures. Figure 3 shows a downpour simulation in the municipality of Almere (Ministry of VRO, 2025b).

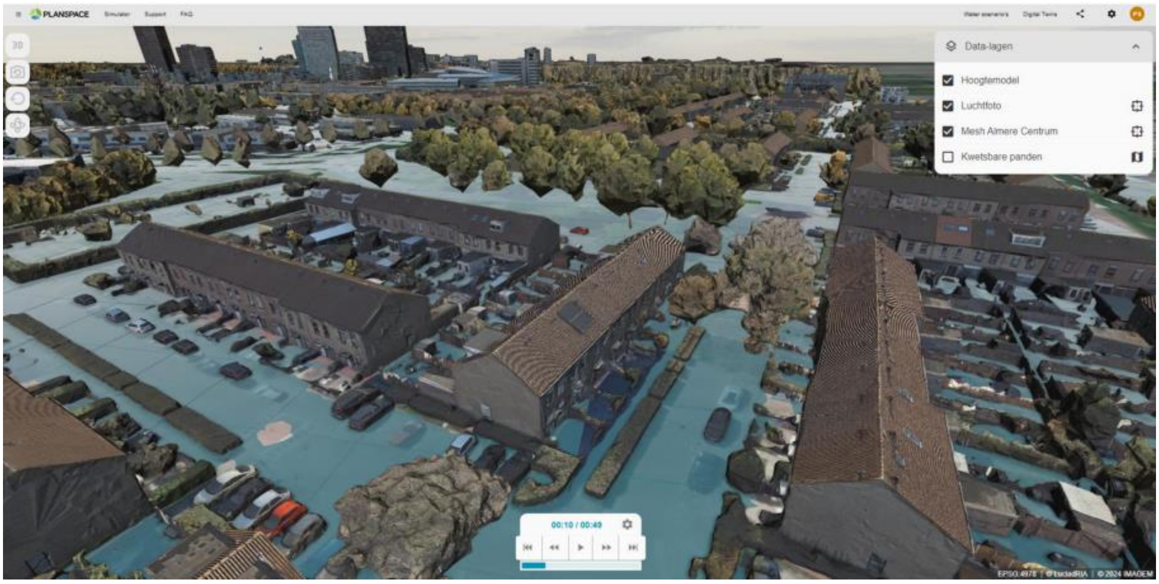

Figure 3 – Simulation of flooding in Almere (source: freely based on Hexagon Neelen and Schuurmans).

In addition to flooding in cities, the digital twins are also used for our water safety. After the catastrophic dike breakthroughs in Zeeland in 1953, we started the fight against the water. What happens in the event of a breach of a dike? How does a water barrier behave under different current and wave conditions? From the 1950s onwards, the watercourse expert laboratory (now part of the Deltares research institute) carried out practical tests with scale models for this purpose. Today, such simulations are performed using computer models in which calculations are performed based on mathematical descriptions of the main processes. Digital twins are particularly suitable for simulating and imagining the consequences of floods. Based on assumptions about, for example, the height and duration of the high water, the size of the hole in the dike, the location of buildings and waterways in the area and the measures taken by the water authority, it can be indicated what the possible consequences of dike breakthroughs are.

With flood models and 3D visualization techniques, digital twins show where and when the land floods in the event of a simulated dike breach. The results of flood models are combined with data on the road network, the (height of) buildings, the demographics and vulnerable installations. Information that is also useful for e.g. evacuation scenarios because insight can be given into possible escape routes and the risks around and safety of buildings and vulnerable population groups.

2.1.4 Definitions of Digital Twins

The various examples indicate that it is not so easy to give an unambiguous definition of a digital twin. Below are three commonly used, international definitions of the concept of digital twins related to different applications in the physical environment:

1. 'digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization'; (ISO/IEC, 2023)
2. A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin." (National Academies of Sciences, Engineering, and Medicine, 2024); and
3. 'digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city, and their related processes.' (Gartner, 2024)

The definitions have in common that they name the digital representation of reality, but they differ in the aspect of reality considered and the degree of integration between its constituent components. Two definitions highlight the data connections that link the model and reality. This is an aspect that plays especially in the display of existing objects as in our first application example. Such data flows are less prominent when using simulation models for future situations as we discussed in the second and third application examples.

In this report we use the more general definition from the letter to the House of Representatives of the Ministry of VRO on the multi-annual vision 'Looking at the Netherlands: Working together on a data-driven approach to the physical environment' (Ministry of VRO, 2024):

> "A digital twin of the physical environment is a digital representation of the urban and rural environment based on data, models and visualizations. These can be used to simulate and analyze different aspects of the physical environment."

This definition indicates the main functions of a digital twin: representation, simulation and analysis. These functions are more extensively reflected in the conceptual model Figure 4 that reflects a more process-oriented view of a digital twin. The figure depicts the interaction between the actual physical environment and the digital twins.

We capture the objects and processes from the actual physical environment in the form of data, models and visualizations. In this way we arrive at a description of the physical environment in a current twin. This leads to an evaluation of the current situation and the possibility to predict and simulate with the same (and other) models and algorithms (including AI). Simulating and predicting also creates the scenarios of the future twins. After that, detail design and engineering will continue to shape the future twins. This is necessary in order to ultimately demonstrate the effects of interventions and interventions in the real physical environment to all stakeholders, so that the decision-making necessary for initiating the change (s) can be carried out optimally. Finally, that decision-making will or will not lead to implementation in the real physical environment. The implementation of interventions leads to adjustments in the data, models and visualizations of the current digital twins. And with that, the circle is more or less round and the process begins again.

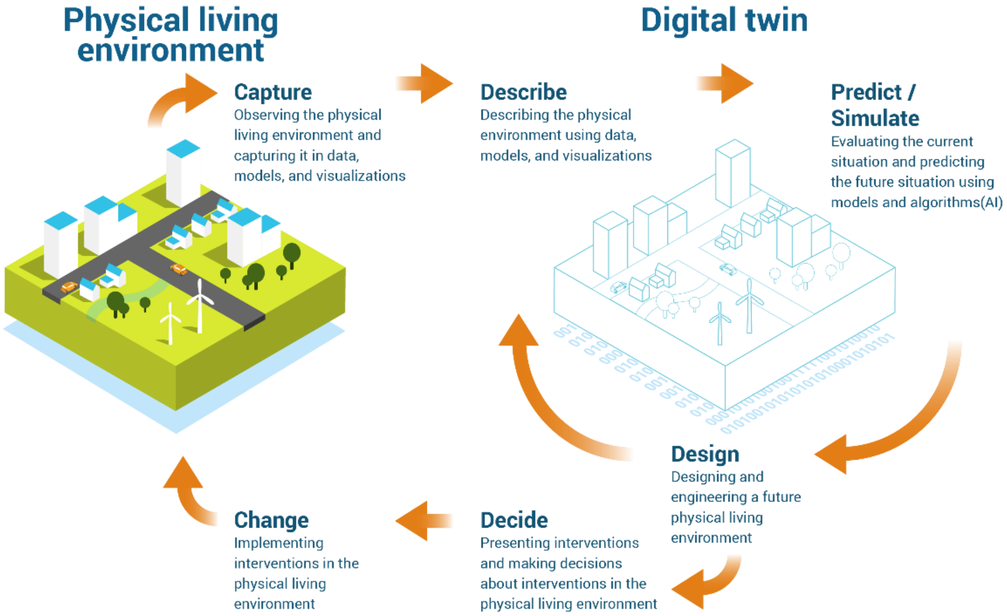

Figure 4 – The main functions of a digital twin of the physical environment.

The flow of data about the characteristics of the physical environment and the daily behavior of people together make the digital world. In that digital world, we then make the simulations and predictions and make decisions based on them, which in turn lead to interventions in the physical environment. In our opinion, this interaction between data and interventions is the core of the digital twin.

2.2 Building digital twins

In addition to this process-based view of the concept of digital twins, the structure in the main components or basic components for digital twins can also be considered (see Figure 5).

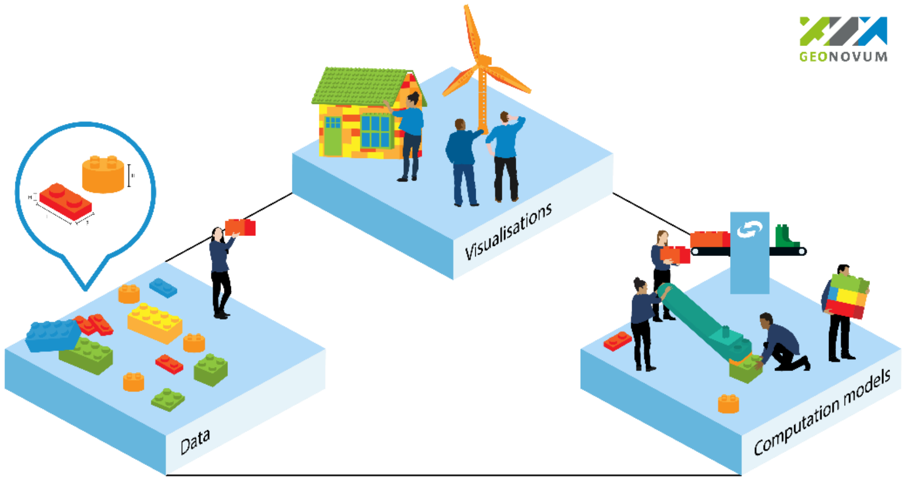

Figure 5 - The three basic components of digital twins: data, computation models (data processing) and visualizations.

By data we mean various data sources: from geographical data (buildings, topography, aerial photographs, etc.) to mobility data, energy data and environmental data. A distinction is often made between static and dynamic data based on the actuality and variability of the data. For example, data from sensors is seen as dynamic data because sensors continuously perceive and generate data.

The component models include computation models, which are necessary to process the data into interpretable information. In addition, computation models represent the knowledge we have of the complex - physical, natural and social - processes in reality. The computation models often consist of mathematical formulas, logical calculation rules and/or AI models. The models are fed with data from physical, natural and social reality and are calibrated and trained for monitoring, simulation and prediction.

In order to make the large amounts of data and results of complex computation models transparent and therefore usable in practice, visualizations are needed. Visualizations and visualization tools such as 3D-GIS, animations, dashboards, XR tools (augmented, virtual and mixed realities) and gaming tools are indispensable components to support the monitoring, planning and decision-making processes with clear and easily interpretable computer graphics and visuals.

The three components, which are interlinked, originate from the reference architecture for European local digital twins(European Commission, 2023). A digital twin combines multiple technologies, such as data analysis and AI, enabling predictive and simulation models that can be updated and modified as their physical equivalents change. In the reference architecture for European local digital twins, a local digital twin is considered a system of systems (Figure 6). The digital twin is a software representation with which interaction is possible. The digital twin as a system refers to other systems with which it interacts as subsystems, because they have their own purpose without the need for a digital twin. The system uses data (services) and computation models, which are derived from existing sources (data and computation models).

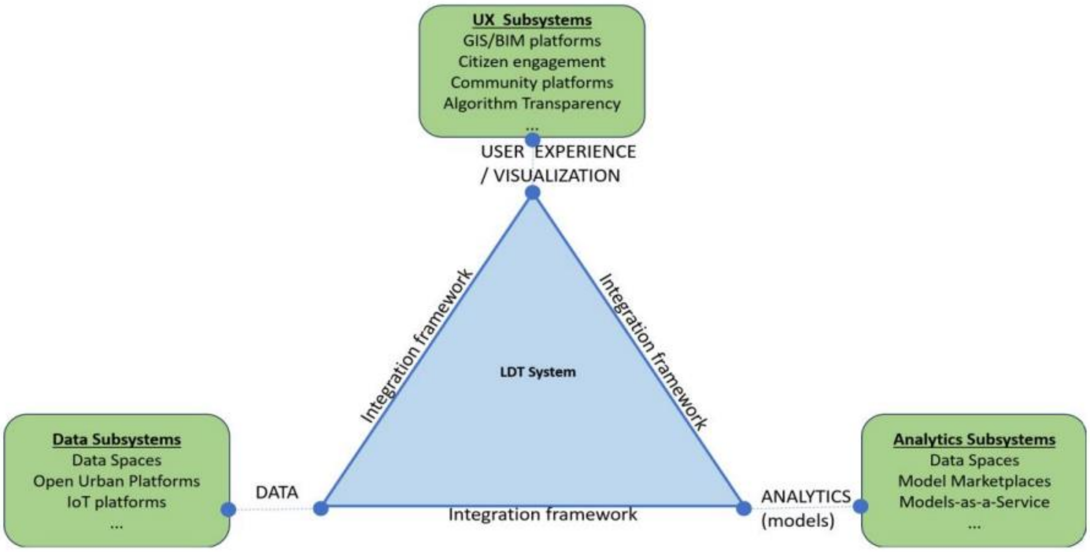

Figure 6 - The digital twin as a system of subsystems(Lohman, et al., 2023).

These data and computation models and associated services may also exist outside the digital twin as a software system, but must have a defined interaction with each other. These sources may include Open Urban Data Platforms, IoT, cloud platforms, Open Data APIs, static datasets and data spaces. Although a digital twin must interact with these subsystems, their technical internal requirements are defined beyond the reach of the digital twins. The same goes for combining data analysis and AI tools. In addition, a digital twin domain addresses cross-cutting issues and provides suggestions that can bring about impactful changes in the community, with continuous change of data and environment.

2.2.1 Digital twins as a configurable system

A digital twin as a system must be able to make efficient use of the various subsystems it needs. In order to be resilient and reliable, tight management agreements must be made. The system must be able to orchestrate the interactions and processes of the subsystem and maintain (or require) interoperability with its subsystems. This requires standardization and agreements so that the interactions between the subsystems are synchronous and organized. To facilitate the realization of digital twins, technology-independent reference architectures are available, among other things, with the underlying functional and technical building blocks to design and implement digital twins (Digital Twin Consortium, 2022; European Commission, 2023). These building blocks help define the three generic components data, computation models and visualizations, which are used to compose digital twins. The building blocks relate to the many functionalities required for the realization of system functionalities for digital twins[7]. This approach to (application) development of digital twins is based on the configurable enterprise architecture pattern (Digital Twin Consortium, 2022). Composite or composable digital twin applications focus on faster time-to-value, service-based orchestration and reuse of packaged capabilities to develop and adapt applications as business requirements evolve. Digital twin building blocks are modular combinations of technical capabilities, which are presented as bundled services. These are orchestrated together (controlled) via a platform to deliver digital twins for specific applications. An important feature of a ‘composable’ digital twin is that it is usually a combination of possibilities from multiple technology suppliers. Composite or system-of-systems digital twins are based on an ecosystem of functional capabilities rather than a single vendor.

[7] A building block model is not a reference architecture. It highlights the building blocks for configurable digital twins and supports multiple architecture approaches, which end users may have developed using their own business standards.

In order to support policy-, planning- and decision-making with a digital twin, the functional possibilities must first be determined in general terms. These functional capabilities are classified by the Digital Twin Consortium (DTC) in a periodic table shown in Figure 7[8]. These are independent components, which have the ability to perform certain actions or achieve certain results in a digital twin (Digital Twin Consortium, 2022). The various purple-designated building blocks in Figure 7, which fall under the heading of analysis, concern the functionalities related to the use of computation models in digital twins.

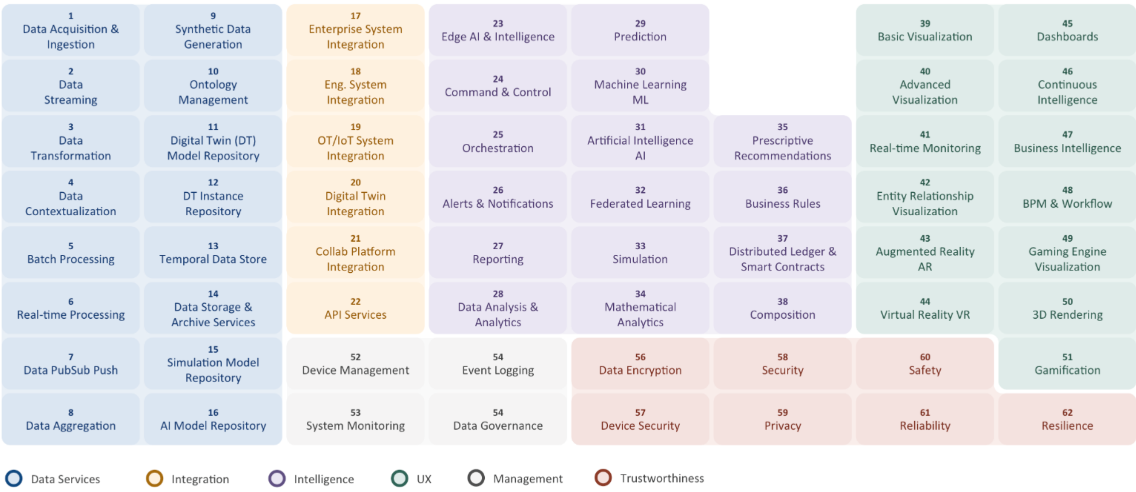

Figure 7 – Periodic system of functional capabilities for digital twins (Digital Twin Consortium, 2022)

Building on the Periodic Table of Functional Opportunities, (European Commission, 2023) the European Commission[9] has set up a toolbox for local digital twins, which is presented in Figure 8. Computation models also play an important role in this framework. Various building blocks[10] related to computation models are included and developed for implementation, such as a model service connector module as data space connector, model catalog, model abstraction service, simulation model, prediction model, AI & ML models, federated learning service.

[8]This overview follows the logic of the periodic system of elements that arranges the building blocks of molecules.

[9] The international DTC has developed the Capabilites Periodic Table (CPT) as an architecture and technology agnostic requirements definition framework. It is intended for use by organizations that want to design, develop, implement and operate digital twins based on use case capacity requirements and compare them with the features of technological solutions. The framework focuses on the requirements for functional building blocks of individual use cases. These use cases can then be aggregated to determine the overall capacity requirements, the digital twin platforms and other technological solutions needed to meet the specific business needs.

[10] The European Commission (2023) speaks of building blocks instead of functional capabilities or capabilities or capabilities as in the Digital Twin Consortium (2022). We use the terms here as equivalents for convenience.

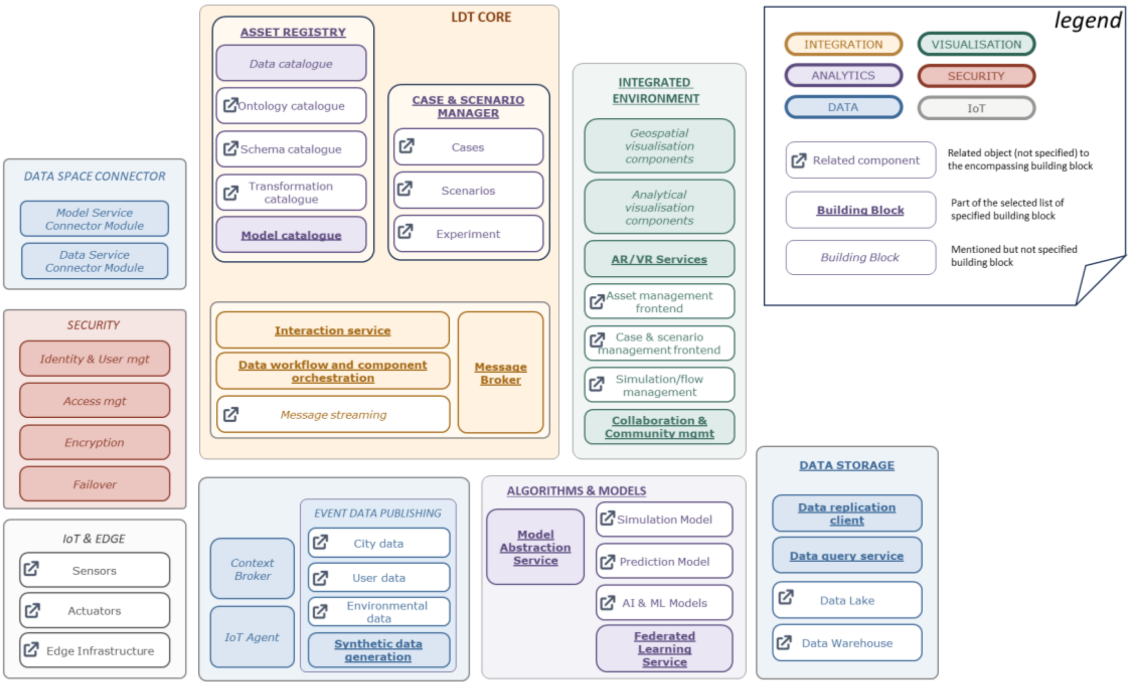

Figure 8 – Functional building blocks for European local digital twins (European Commission, 2023)

Why are these frameworks of functional capabilities so relevant to working with computation models and digital twins? These frameworks play a crucial role in setting up a flexible and scalable ecosystem for digital twins. Building blocks are the fundamental components that enable digital twins. The relevance of building blocks lies in their flexibility and reusability. By using modular building blocks, digital twins can be easily customized and optimized for different applications. This promotes interoperability and makes it possible to reuse existing building blocks, which reduces costs and development time.

The use of a capability framework facilitates the structured identification and improvement of the various functional capabilities of a digital twin. This allows organizations to determine which capabilities are essential to their applications and ensure that they choose the right building blocks to meet the functional needs of users. Also for working with computation models and digital twins, various building blocks and capabilities have been differentiated in these capability frameworks.

Both the DTC capability framework (Digital Twin Consortium, 2022) and the EU Local Digital Twin Toolbox Building Blocks (European Commission, 2023) provide a detailed set of building blocks, which are important for the functioning of digital twins. These frameworks help define the key aspects of digital twins, from data integration to managing the entire life cycle of digital twins. It enables organizations to seamlessly integrate different computation models and data into a common ecosystem of digital twins. The frameworks also highlight the importance of interoperability, as digital twins often consist of multiple applications, systems and models that need to be able to communicate with each other.

Both frameworks thus provide a structure for identifying the necessary capabilities of computation models, which the digital twins must support. This helps to ensure that digital twins are not only operational, but also able to work effectively with different types of computation models, which are needed to analyze and manage the physical living environment.

2.2.2 Modular architecture

Interoperability also involves the ability of different computation models to work together and complement each other's functionality to perform complex tasks. This can be achieved by developing modular computation models, which perform specific tasks and can be integrated into digital twins. In a modular architecture for digital twins, computation models are developed as separate components, which can be easily combined (European Commission, 2023). In a digital twin, which is set up as a modular platform, it becomes possible to reuse individual computation models and components in different workflows and applications. Computation models are shared via repositories with documentation, so that users can easily integrate existing models into their own applications and workflows. In order to facilitate the deployment of digital twins, the Ministry of VRO is gradually working on a national network of local digital twins with the Digital Twins program.[11] Such a system should increase interoperability. An architecture group is now developing a reference architecture[12]. The reference architecture includes a series of reusable building blocks for digital twins.

Intertwin Digital Twin Engine and FloodAdapt

FloodAdapt is a digital twin developed by Deltares that aims to promote and accelerate flood adaptation planning. The system integrates flood models and detailed impact models with a user-friendly interface, allowing non-experts to calculate and evaluate various scenarios, future conditions and adaptation options within minutes. FloodAdapt thus bridges the gap between scientific development and the practical application of climate adaptation to floods anywhere in the world. FloodAdapt uses the necessary thematic and core modules of the interTwin Digital Twin Engine (DTE) developed to enable digital twin builders to easily deploy FloodAdapt in any desired geographic region. With interTwin, developers can build digital twins for complex flood modeling on a federated computing and data infrastructure. Users can then effectively use the output of the digital twins to make informed decisions, either by exploring pre-built visualizations and data analytics through an online dashboard, or by developing custom analytics.

InterTwin is a European Union-funded initiative that focuses on designing and prototyping an interdisciplinary Digital Twin Engine. This initiative provides a common approach to the implementation of digital twins that is applicable within various scientific disciplines, such as physics or the environment. This open source platform offers generic and tailor-made software components for modeling and simulation, with which specific digital twins can be assembled. The specifications and implementation of the DTE are based on a jointly designed conceptual model, the DTE Blueprint Architecture, which is guided by the principles of open standards and interoperability.

To achieve a working solution architecture, we work from core values that outline how interoperability and alignment are pursued. They are general rules for architecture, drawing up not only technological but also organizational and social rules. For the practical organization of architecture, several function blocks have been appointed, which are elaborated in five working groups: data & sensors, computation models, visualization and foundation (catalogue, IAM). Instead of a hamburger model for architecture consisting of several horizontal layers, a triangular model is used. (Lohman *et al.*, 2023) This model has a loose connection between the function blocks for data and data services, computation models (data processing with intelligence), visualization and User eXperience (UX) and the foundation containing management and aspects of access control and trust.

2.3 Stages of completeness

Digital twins are now widespread in the Netherlands (see, for example, Van Apeldoorn et al., 2023). However, a first look at the multitude of applications also indicates that this concept can have a completely different meaning for different users. We will elaborate on this diversity in the next

[11] https://zichtopnl.nl/digitaltwins/
[12] https://geonovum.github.io/NLDT-Architecture/

chapter. To introduce this, it is important to consider the different layers from which a digital twin can be built up to describe the physical environment.

The literature on digital twins for smart cities distinguishes between six layers that can make up a complete digital copy of a city (White *et al.*, 2021, see Figure 9). The base layer describes the physical subsurface on which the city stands, such as soiltypes, altitude and watercourses. This can easily be displayed in a two-dimensional map. Buildings (layer 1) and infrastructure (layer 2) are successively placed on this base layer (layer 0). With this addition, a complete, static image of the city can already be given, especially if a realistic three-dimensional view is chosen. By then also adding real-time data on people, vehicles or goods (layer 3) and other data on air quality (layer 4), for example, a dynamic image is created that can be used to monitor how a city functions. In a final layer (5), simulation can be added to show possible changes in the system, for example to show the consequences of a city expansion or adjustments in the infrastructure.

Publicly accessible digital twins of the urban environment that can be accessed via web interfaces, for example, often consist of layers 0 to 2. Although there are also fine examples in development in which layers 3 and 4 have been added[13]. Computation models mainly play a role in the last layer of this smart city example and these are available in tools as described in sections 2.1.2 and 2.1.3. The present study focuses on the application of computation models in digital twins and does not look so much at the applications that mainly unlock existing data layers. Of course, digital twins in other application domains (rural area, subsurface) have different elements than in this smart city example, but there too a distinction can be made in increasing complexity if dynamic data layers or simulation models are added.

[13] An example is the digital twins of the municipality of Alkmaar: https://dtp-alkmaar.azurewebsites.net/twin

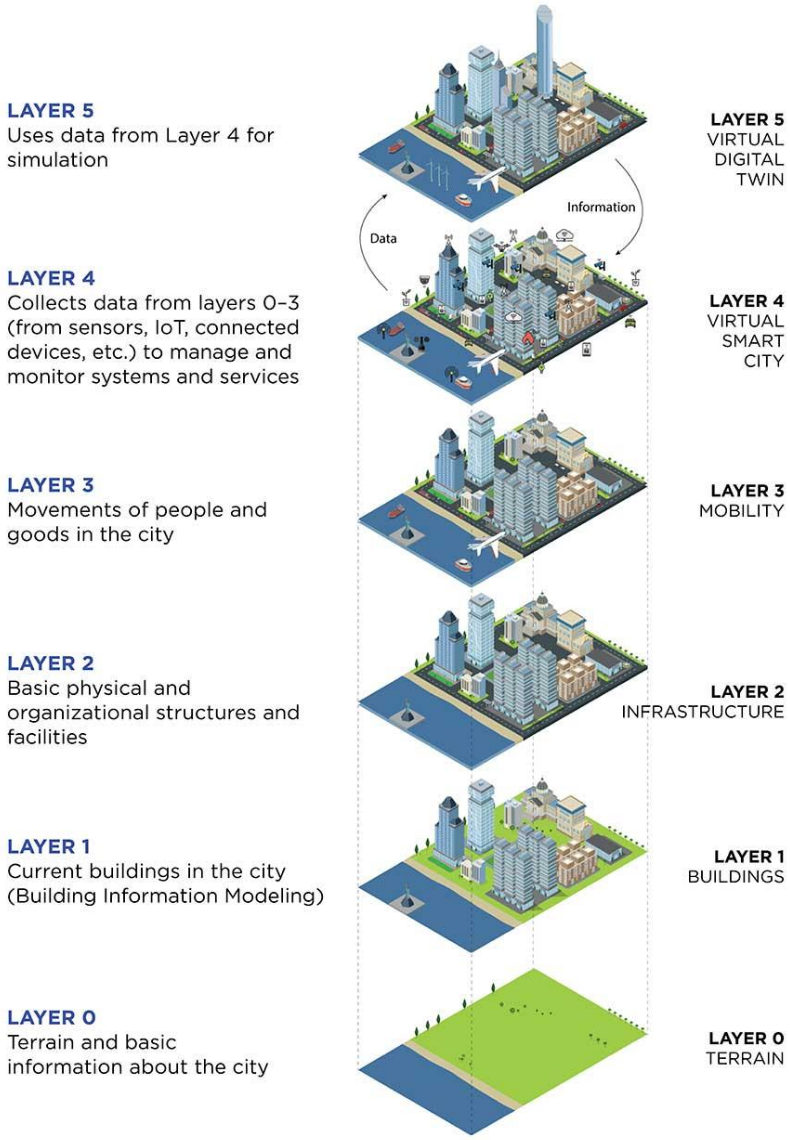

Figure 9 – The six layers of a complete smart city digital twin. (White et al., 2021)

The layers of completeness in this schematic representation can also be referred to as level of maturity (Metcalfe et al., 2023) or degree of complexity (Van Apeldoorn et al., 2023), but those designations incorrectly give the idea that there is a growth trajectory that must be followed in all cases. That is of course not the case, because as with any tool, the choice of a suitable tool depends on the application. After all, each question requires its own set of instruments, depending, for example, on the spatial or timescale at which the question is addressed, the (effect) relationships that are important in this regard and the desired accuracy. For spatial issues that play on a coarse spatial scale and long time scale (do we prefer to build the desired 1 million homes in the Netherlands in view of climate change?), you choose a different model than if you are interested in local effects in the short term (what are the effects on air quality of closing a specific street in a city). The desired completeness and way of visualizing in the digital twins will also depend on the question that arises. For long-term strategic spatial issues, real-time data layers (layers 3 and 4) are not very relevant, while they are crucial for other applications.

3. Computation models

3.1 Computation models in digital twins

Describing the physical environment in a digital twin starts with creating and/or gathering data to paint a current picture of reality. The raw data is processed into usable data or information to make decisions about the physical environment. To support these decisions, computation models are often used that provide a simplified representation of (certain aspects of) reality. Models for the physical environment are nowadays mostly computer models, which summarize reality in mathematical formulas. The computational power of computers is then used to make a calculation with observations of reality (data) and to calculate results. That is why we speak of computation models. Computation models, which are part of a digital twin for the physical environment, often describe a specific aspect of the physical environment. Combining different models creates a more complete picture of reality. Such a combination does require that the individual components are linked in a logical and consistent way that matches the way in which objects, processes and systems in the physical living environment relate and function. Only in this way can cause-effect relationships be imitated in the right way.

The major challenges in the physical environment, such as the housing challenge, energy transition, climate adaptation and the transformation of agriculture are complex in nature. Not only as a task itself, but also because of the interconnectedness and influence of tasks on each other. Computation models can help to understand the complexity of the task, to analyze interdependencies, outline potential future developments, or determine the possible consequences of proposed interventions and decisions. They simplify the complex reality and can provide insights that are not directly visible in separate collections of observations. With models it is possible to simulate difficult issues in the physical living environment, for example mimicking developments that are not possible in reality, because they are too expensive, too complex, or not possible in time. Models help to gain insights into relationships and relations, into the calculation of the outcomes of alternatives and scenarios and into the possible consequences of decisions to be made.

Because computation models are often created for a particular question or problem, they are usually created specifically for a particular application domain. In the various areas of application of the physical living environment, many types of computation models can be found, such as energy demand and supply calculations for the energy transition, climate adaptation models to calculate waterlogging or heat stress, or demographic models for estimating future housing needs. Various types of models are used for this purpose; physical-spatial models, behavioral models, economic models and decision-making models. These are many different and very diverse computation models, which are made by or on behalf of governments by companies (often specialist engineering firms) and public knowledge institutions. In addition to being a very data-rich country, the Netherlands is also a very model-rich country.

In the following sections we will discuss various aspects of creating and using computation models in digital twins for the physical environment. This introduction aims to understand the variety of computation models and to better understand the (im)possibilities of using such models in digital twins. Understanding which types of computation models exist is necessary to determine which models can be used for problems and issues. This overview will hopefully also contribute to a wider use of models in digital twins. First of all, we look at the different steps in drawing up a model. Then we go into the variety of types of models and look at the purpose they can have (function), the way they are set up and describe their part of reality (approach) and their domain of application.

3.2 Modelling

Computation models for the physical environment are almost always fed with observations about reality (data). This data is processed into outcomes in a number of steps. That process can be considered as a cyclical process as shown in Figure 10. The most important steps in creating a computation model are:

1. Analyzing reality in a conceptual model;
2. The coding of the conceptual model in a computer model;
3. Drawing up an application model for a field of study;
4. Simulating an outcome with the application model.

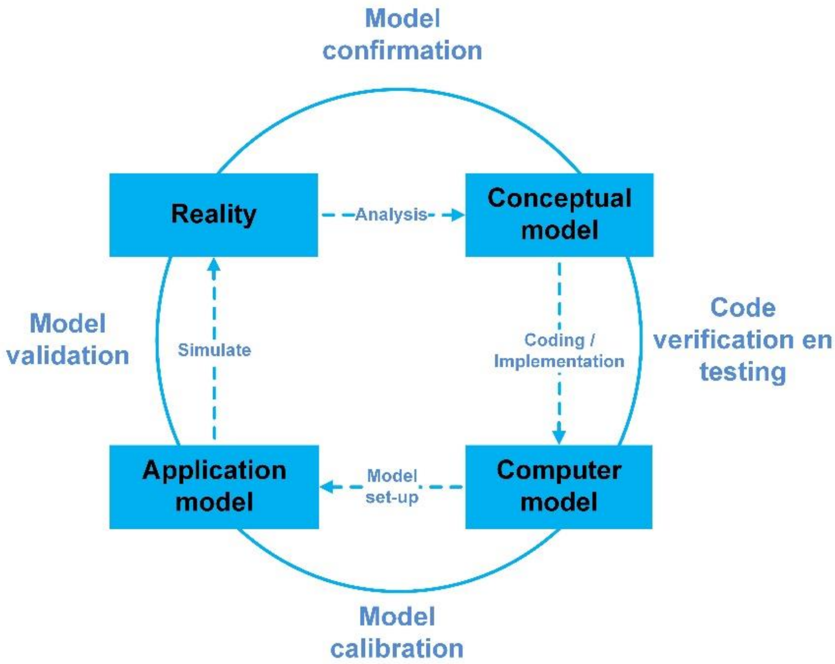

Figure 10 - Modelling as a cyclical process (freely based on Refsgaard & Henriksen, 2004).

Modeling starts with describing (part of) the physical living environment in a conceptual model. That conceptual model describes reality in terms of the most important elements in the considered part of the living environment and the relationships between those elements. These relationships are established after an analysis of observed patterns and processes and then quantified in mathematical equations. This conceptual model is based on the user's perception of the main processes in the field of study (perceptual model) and the associated simplifications and numerical representation thereof that are considered acceptable to achieve the purpose of the modelling. A conceptual model describes the system elements, processes, structures, characteristics, etc. that are necessary for the specific purpose of the modelling.

Freely translated, a conceptual model is a simplified representation of how one assumes that a real system behaves, based on qualitative data from reality. An elaboration of a conceptual model contains initial calculations for the most important processes. A conceptual model is established through a clear question or objective and an analysis of observations and area knowledge and data from the field or databases. The basis of computation models is therefore often the best available scientific knowledge about the functioning of the processes in the physical living environment.

The second step in the modelling process is then the elaboration of the hypotheses (relations) from the conceptual model using model code. This coding gives a formalized elaboration of the described relationships, which can be read and executed by a computer. Such a computer program is so generic that, without program changes, it can be used to create a computation model for different fields of study. It then uses the same basic equations but with different input dates and possibly also different parameter values. The complexity of model code can range from simple calculations based on a few mathematical equations to a very comprehensive computer code. In a process of code *verification,* the model code is tested for the extent to which it is an acceptable representation of the conceptual model and not directly whether it also accurately mimics reality. The outcome of this second phase is the *computer model.*

The computer model is then used to create a location-specific model for a particular study area, including input data and parameter values. In this third phase, the *model calibration takes place:* the procedure of adapting parameter values of a model to reproduce the response of a given study area within the range of accuracy specified in the performance criteria. Setting up a location-specific model using a model code requires, among other things, the definition of boundary and initial conditions and parameter assessment from field and laboratory data. This is how the *application model is created.*

In the fourth and final phase of *model validation, the results of the application model are* compared with the original observations. This is the ultimate substantiation that the model has a satisfactory range of accuracy and consistency within the scope for the application of the model. The extent to which the display is acceptable depends on pre-specified limits and corresponding accuracy ranges. These requirements can vary considerably from one field of application to another. For a scenario-related, large-scale estimate of housing needs in 2050, different requirements apply than for determining the noise load on a sensitive object as a result of a planned new road. The complexity of the model code and the choice of the final model also depends on the requirements imposed on the results of a model.

During validation, it is important to pay attention to sensitivity and uncertainty analyses of the model predictions. If after the validation step it turns out that the model does not mimic reality well enough, or if reality has changed in the meantime, the modelling chain can be followed again. A first step in this is *model confirmation:* confirm that the conceptual model contains the right elements and describes the processes and their interdependence in a correct way. The subsequent steps of coding, drafting and simulation can also be considered again in order to achieve a better result. This reflection on previous steps makes building models an iterative process.

The validated model can generate outcomes with which, for example, policy can be developed. In these applications, results are generated in consultation with end-users that explore, for example, possible developments (trends, scenarios), desired final images (optimization) or effects of certain interventions (what-if applications). In the following sections we will go into more detail about the different types of models, their functions, the approaches used and common application domains.

3.3 Types of computation models

Computation models exist in many types and species and it is impossible to give a complete overview of all computation models, which have been developed to describe and simulate issues in the physical environment. Even drawing up unambiguous typology is difficult because computation models can differ from each other in many aspects. The differences between computation models do not only concern the application domain and purpose, but also, for example, whether a computation model is static or dynamic. Static models count towards the end result in one step, while dynamic models work with intermediate steps over time. On the basis of these interim steps, the following situation is calculated again and again. These types of models therefore take into account developments and interactions that occur during the simulation. In addition, both a deterministic and a probabilistic approach can be used when simulating a process with a computation model. A deterministic approach applies strict cause-effect relationships, while a 'probabilistic' approach calculates the probability that a state or action will result. Furthermore, computation models can also differ in the way they describe processes, for example as the result of interrelated local events (bottom-up), or precisely as a result of top-down developments. But you can also characterize models in the way in which computation models are specified (based on empiricism or theory) or the way in which outcomes are calculated (as continuous or discrete values).

The TU-Delft system modelling wiki (2024) elaborates on this diversity. In the rest of this chapter we discuss the diversity of models on the basis of some aspects, which play a role in the creation and use of computation models. In doing so, we look at: the function (purpose) of the model, the model approach that simplifies reality and the domain of application. Figure 11 visualizes this distinction which is explained in more detail in the following sections.

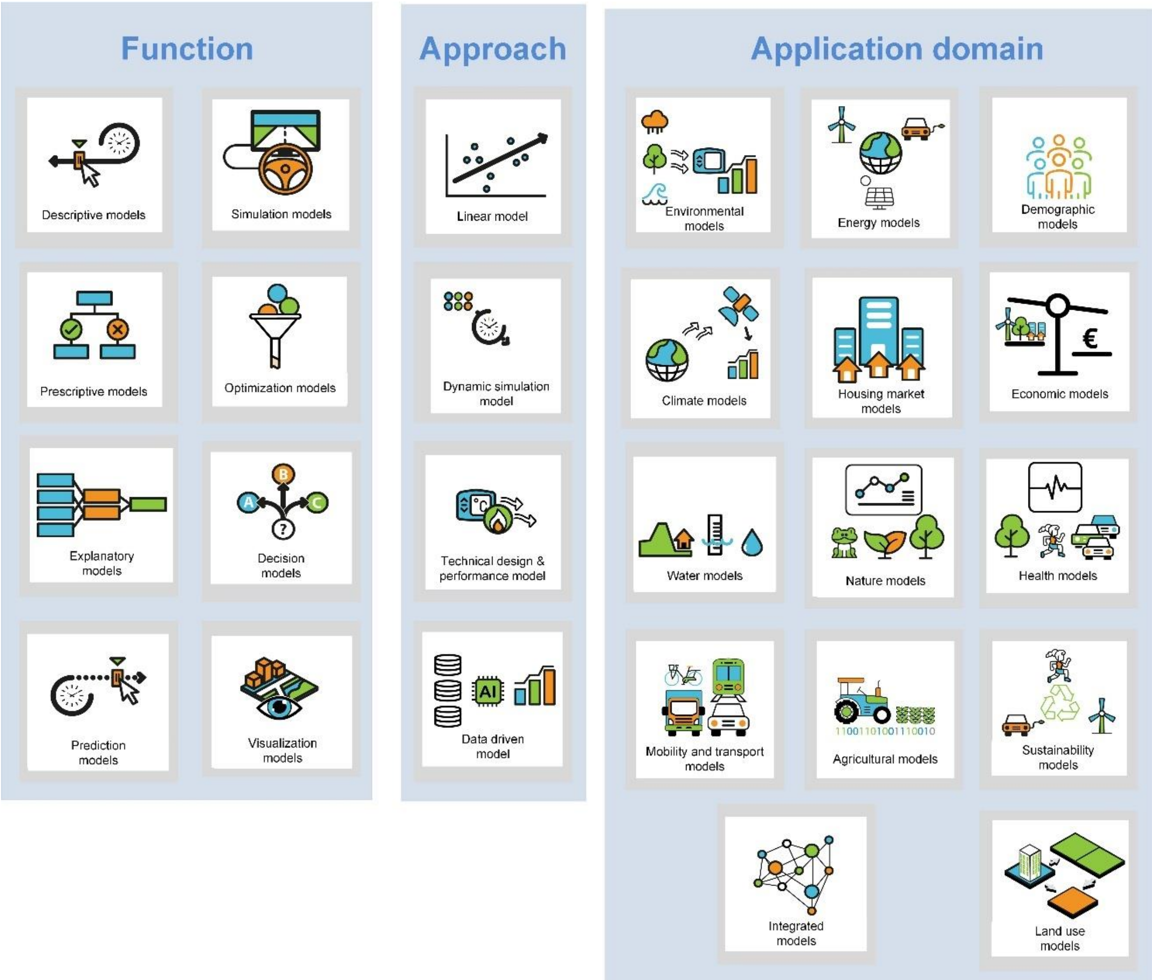

Figure 11 - Computation models classified by function, model approach and application domain.

3.4 Computation models by function

Computation models for the physical environment are made with a specific purpose in mind. They often have a defined function in the decision-making on issues in the physical environment. For example, to describe the current context in which a decision must be made, to predict possible future situations, or to generate optimal solutions. Based on different goals and functions of computation models (Edmonds et al., 2019), we can distinguish a number of different model types:

1. Descriptive models
2. Prescriptive models
3. Explanation models
4. Prediction models
5. Simulation models

6. Optimization models
7. Decision models
8. Visualization models

Of course, models often have more than one function. For example, a descriptive model can also be used for predictions. The way in which a model is used therefore depends on the question and the goal you want to achieve, but also on specific properties of the computation model. After all, few computation models will be suitable for all different functions. If that is suggested, it is doubtful whether the model for each function is also the best available model. Below we give a brief description of each of the different model functions. We illustrate these functions with examples of operational computation models for the physical environment.

A *descriptive model* is intended to represent the state or functioning of a phenomenon or event now or in the past. A histogram of wind speeds at Schiphol, a map of current flight movements over the Netherlands,[14]or the schematic description of the subsurface in the Netherlands (see Figure 12) are examples of descriptive models. Many dashboards that are currently being developed by governments and in which current information about the living environment is shown can be regarded as a descriptive model.

A *prescriptive model* is intended to indicate how we should act, for example because of a certain standard or legislation, such as in the environmental law, in which a permit is applied for on the basis of a prescribed decision tree[15]. Prescription models are often displayed in the form of flowcharts, decision trees and decision rules.

An *explanation model* tries to understand a certain phenomenon or event by using the (explaining) variables that influence it. It indicates to what extent these variables contribute to the occurrence of the event. This can include, for example, explaining choice behavior (which explains that an individual chooses a particular mode of transport or for a company for a sustainable investment), locations of developments (new distribution centers, forest loss, traffic accidents) or quantities (traffic flows, house prices). Classic examples of these types of models are statistical (regression) or machine learning models. Often explanatory models are also suitable for predicting events. After all, the factors that were important in the past to explain an event can also provide a good indication for future events. With such insights, empirical models can be set up that extrapolate trends from the past. Such models are particularly suitable for short-term forecasts where uncertainties are not very high.

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[14] See https://bas.flighttracking.casper.aero/

[15] See https://iplo.nl/news/2022/digitalisation-map-restricted areas/

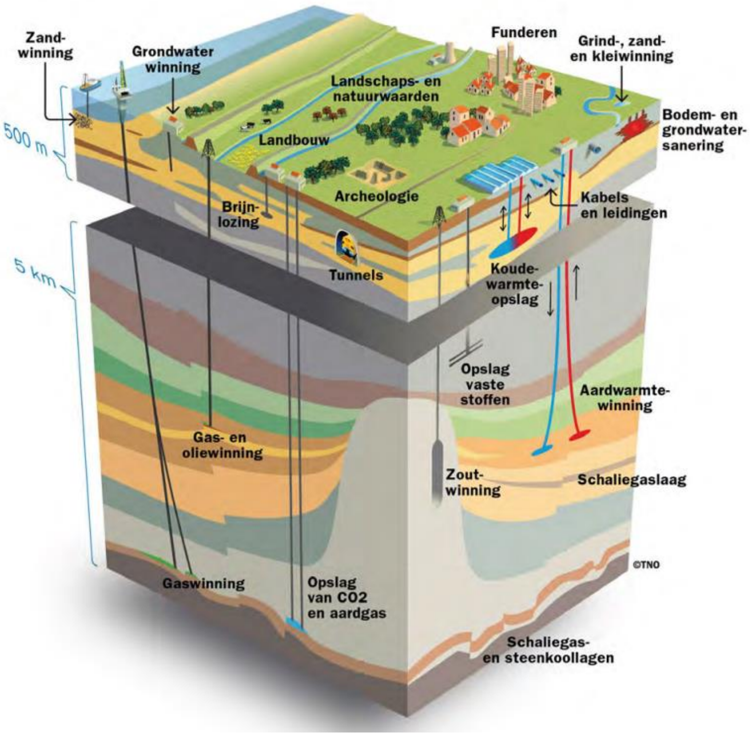

Figure 12 - Descriptive model of the subsurface (after IW & EZK, 2018).

Prediction models are computation models that try to say something about the future based on data and knowledge from the past and the present. For this, it is necessary to make assumptions about the future. The simplest assumption is that processes from the past continue undiminished, but more often assumptions are added about future changes in the variables that control the system. This may include assumed changes in population size, greenhouse gas concentrations and so on. The results of prediction models often have a large margin of uncertainty, because the assumed changes in the floating variables are uncertain and the understanding of the system studied is often incomplete. These uncertainties are logically greater if the system is more complex and is thought ahead for a longer period of time. A typical example of forecast models are the weather models of the KNMI (ECMWF[16] for Europe and HARMONIE[17] for the Netherlands), which generate weather forecasts eight times a day. Another example from a similar domain concerns climate models, such as those used by the Intergovernmental Panel on Climate Change (IPCC), which simulate global changes in, for example, temperature and precipitation up to 2100. In such cases, of course, uncertainties are many times greater and scenarios are often used, describing coherent assumptions about the key variables in the climate system.

A *simulation model* mimics reality and shows how it develops over time from a given starting situation. This is actually a specific form of prediction, which mainly focuses on defining the rules according to which change takes place. In their most typical form, these are very dynamic models, which are especially strong in reproducing processes that are highly variable in space and time. The emphasis is less on a comprehensive explanation of how a system works exactly, but more on mimicking the behavior of those systems as well as possible. Such simulations can be especially

[16] https://www.ecmwf.int/

[17] https://www.knmi.nl/research/weather-climate-models

helpful in describing and predicting spatial developments. A typical example is the cellular automata, which are used to simulate changes in space use[18].

Optimization models make calculations to achieve a specific goal as efficiently as possible. This goal is described in numerical form (target function) as, for example, optimizing yields, minimizing costs or emissions. In addition, the framework conditions for solutions are specified (e.g. baseline situation, legal restrictions) and an optimal solution is calculated using numerical methods. Depending on the type of problem to be solved, various methods are available for this, such as linear programming and genetic algorithms. An example of an optimization model is MERIT, which is used to maximize the economic feasibility and robustness of investments in a new technology in the manure chain. (van Wagenberg et al., 2019)

A *decision model* tries to give a balance (evaluation) of advantages and disadvantages for a specific problem situation in order to select a solution or preferred alternative or sometimes even to make a choice. Models that make decisions themselves are scarce, but for example the choice to[19] close the Maeslant barrier is made by a specially developed decision model. More often these models are a tool for making decisions and we also speak of a Decision Support System (DSS). There are many different types of decision models, such as score cards (effect tables), decision trees and decision tables and multi-criteria analysis. Multi-criteria analysis (MCA) is an evaluation method to make a rational choice between various discrete alternatives based on multiple criteria. With MCA, scores on economic, environmental and social criteria can be added together and weighed up. The MCA method is similar to social cost-benefit analysis (CBA) which is widely used in the balancing of large public investments, but in MCA criteria do not need to be expressed in monetary terms (euro).

Visualization models are models that display the results in one, two, three or four dimensions. They are often specific tools to show outcomes from other models in an appealing way. Based on their geographical location, underlying model results can be processed in such a way that they are shown in different dimensions. These are often referred to as GIS models, because this spatial data processing is prepared or performed in Geographic Information Systems (GIS). With 4D visualization, movement is introduced in time, for example via moving images or animations. Visual models can be a strong means of communication, and many digital twins make use of the ability to show model results in 3D. But also visual results always need explanation about the background and assumptions of visualization. Examples of visualization models are the models of the subsurface (Figure 13), included in the Basic Registration Subsurface (BRO):

1. Geomorphological models for landscape shapes (Geomorphological Map);
2. Soil models for specific soil characteristics (Soil Map, GeoTOP);
3. Geological models for properties of the deeper subsurface (Digital Geological Model);
4. Hydrogeological models for groundwater system characteristics (REGIS II and Groundwater Level Depth Model).

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[18] See for example https://spacemodel.vlaanderen/what-we-do/simulation

[19] https://www.rijkswaterstaat.nl/water/water management/protection against water/water barriers/delta works/maeslant barrier

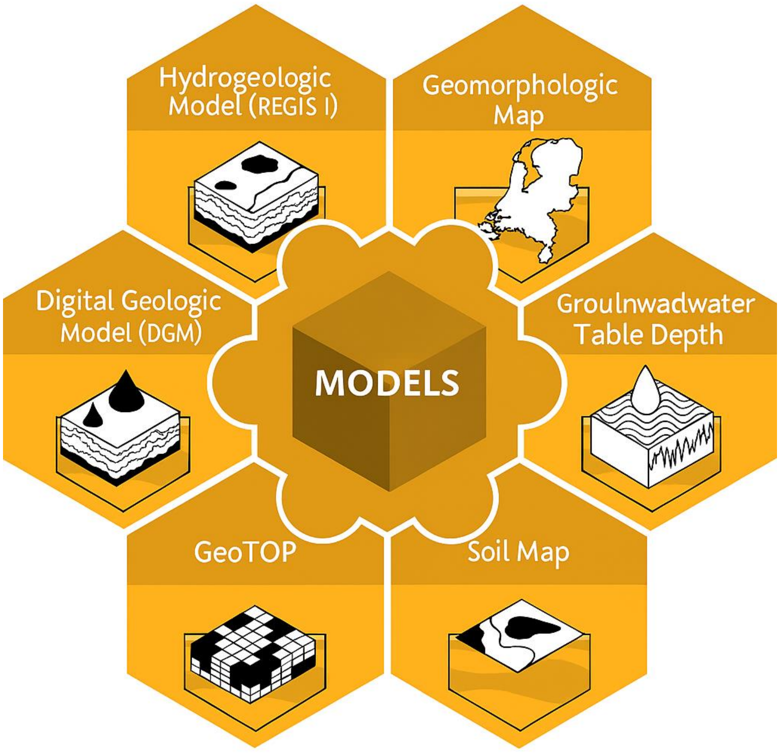

Figure 13 - Visualization models of the subsurface.

3.5 Computation models by model approach

An important aspect that affects the computation model and the multiplication of reality chosen therein is the choice of the model approach that is applied to the computation model. This approach, also called the modelling paradigm, is used to describe the relationships in the system of the computation model. There are many different modelling paradigms, and there are great opportunities to identify modelling approaches. We give a limited, non-exhaustive picture of a much more complex reality of model approaches. Some of the most common are listed below and briefly described for illustrative purposes for the non-modellers. We have always included some examples of operational computation models, which are used in the physical environment.

Linear models are based on (sets of) linear mathematical equations. They are easy and fast to make but cannot display dynamic changes. Important examples of the use of linear models for the physical environment are, for example, computation models for life cycle analysis[20] (LCA models) for calculating the environmental impact that a product or object has on the environment. Another common form of linear models is the so-called input-output models, which economists use, for example, to determine the links between production and a number of economic characteristics, such as energy use and environmental impacts.

Dynamic simulation models describe how a system with its components behaves over time. It describes how a system functions and reaches a certain end state. In their simplest version, simulation models work on the basis of a starting situation with an added amount of change per time step (such as in so-called rule-based simulation models, which calculate for example the amount of erosion, see: Koomen & Stillwell, 2007). These models are therefore sensitive to the initial conditions and described system structure. More complex examples of this can be found in system dynamics and actor-based models. An example of an actor-based system is TNO's Urban Tools

[20] https://www.rivm.nl/en/life-cycle-assessment-lca

Next in which it experimented with calculating scenarios for, for example, destination and transport mode choices and parking behavior of fictitious individuals in the Rotterdam region (Snelder et al., 2021).

Technical design and performance models are used for calculations and predictions of technical systems. Examples are the design of buildings, infrastructure and works of art and the technical systems for, for example, energy management and operation of electronic measurement and control systems in buildings, infrastructure and works of art. An example is the integrated model for the greenhouse construction of TNO (SIOM[21]).

Data-driven models are mainly aimed at processing large datasets ('big' data). These models are helpful in generating up-to-date and accurate information and can also make very accurate predictions. They are completely and critically dependent on the datasets they are trained on and the way results are produced can be quite inscrutable. Such a black box can be prevented by good documentation, but understanding it often requires some expert knowledge from the user. Depending on how the data is processed in such models, one also speaks of artificial or artificial intelligence (AI) models. For the physical environment, these data-driven AI models are used, among other things, for automatic image recognition for object detection and mutation detection based on aerial photographs or satellite images of objects in the physical environment, for example buildings, trees, roads and solar panels.

Which model approach is chosen for setting up a computation model is first and foremost the choice of the modeller. What best suits a specific problem definition depends on the defined criteria, the available data and the available knowledge of the objects or processes to be modelled. None of these approaches are good or bad in themselves, and the choice is often a trade-off between different cost-performance options. The approaches are tools that can be used correctly or incorrectly, and the resulting model may be appropriate or unsuitable for the problem that arises. The modeller must be able to clearly explain why a particular approach is chosen and how suitable it is for the modelling problem.

3.6 Computation models by application domain

Computation models are often made for solving a specific problem and therefore tailored to a specific application domain. Computation models thus reflect the current knowledge about the functioning of (aspects of) that scope. Typical application domains of such sectoral models in the physical environment are environment and climate (water, soil, and air), agriculture, nature and biodiversity, the built environment (construction works and housing market), infrastructure (mobility and transport networks by road, water, rail and air) and water systems.

In addition, there are also more generic models, such as population models, economic computation models, health models, space use models and integral models that try to consider the individual domains in conjunction with each other. In this way, systems are approached as a more complete whole. Below we discuss different application-specific computation models and give some examples of available implementations. This overview is certainly not complete nor intended to make a very clear classification (some models have multiple application domains), but it aims to give an idea of the different types of models that can be used and possibly within digital twins.

For a healthy environment, computation models are made and sensors are used, which map the quality of the physical living environment. These are *environmental models.* Think of sensors that sometimes measure specific substances in air, water, groundwater, soil and solids in real time. Examples include particulate matter from traffic, pesticide use and nitrogen emissions from agriculture and nanoparticles and microplastics from materials used in the outdoor environment. Due to the use of new materials, electronics and insulation, more and more fabrics end up in homes

[21] https://www.tno.nl/en/sustainable/energy-built environment/glass horticulture/system integration/

and offices. Both for the indoor and indoor environment, the computation models are used to analyze the sensor data and to make predictions. For example, computation models help to respond more quickly and precisely to possible contaminants, calamities and health risks for humans, animals and plants in the physical environment. Examples of environmental models are AERIUS[22] for nitrogen deposition, the OPS (operational[23] priority substances) model for air quality, CNOSSOS-EU[24] for noise and SAFETI-NL[25] for the risk calculation of establishments with hazardous substances (external safety). LCA models[26] are also calculation methods for assessing the impact of products and human activities on the environment. Such models look at the entire life cycle of a product or activity; from extraction of raw materials through production and (re)use to waste treatment.

Climate *models* are models that describe the state of the climate and with which, for example, the following of the Paris agreements can be monitored. They are also relevant for analyzing the effects of climate change and evaluating possible solutions. As with environmental models, climate models work with observations and measurements of, in this case, greenhouse gas emissions to the atmosphere are the basis of the simulations. Such measurements often come from satellites. The simulations of future climate change are based on scenario-based assumptions about changes in greenhouse gas emissions. Global Integrated Assessment Models such as[27] PBL IMAGE provide important input for such studies and translate assumptions about socio-economic and technological changes in space use patterns and partly related greenhouse gas emissions. (Doelman et al., 2018) The results of the IPCC's international climate models are translated by KNMI in the Netherlands into possible Dutch climate scenarios[28].

Climate adaptation is about adapting the physical environment to the consequences of global climate change. This is very important for the Netherlands as a delta country. In the computation models of the Dutch climate adaptation strategy, four aspects are important: it gets warmer, it gets wetter, it gets drier and the sea level rises. This leads to:

1. Flooding by the major rivers and the North Sea;
2. Waterlogging due to more and more short, heavy rain showers;
3. Drought;
4. Heat stress in cities in particular.

Water models can be used to determine some of these effects. In doing so, they contribute to well-informed water management that ensures dry feet and sufficient clean water. The Netherlands has a long tradition in making and using water models and therefore there is a wide range of water models available for freshwater and saltwater models, high water models, water quality models. For example, the National Water Model[29] (NWM) is a collection of existing, interconnected water models. These provide insight into the consequences of climate change and socio-economic developments for our water management, both for water quantity and quality. A more specific model environment, suitable for interactive, policy-related applications, is Deltares' D-HYDRO Suite.[30] It enables simulations of floods, storm surges, hurricanes, waves, flooding caused by heavy rainfall, sediment transport and morphology, water quality and ecology. Water models for simulation of flooding caused by heavy rainfall and floods are part of climate adaptation, as well

[22] https://www.aerius.nl/
[23] https://www.rivm.nl/operational priority substances model
[24] https://www.infomil.nl/topics/sound/execution mapping/index/handbook-modelling/
[25] https://www.rivm.nl/safeti-nl
[26] https://www.rivm.nl/en/life-cycle-assessment-lca/what-is-lca
[27] https://www.pbl.nl/en/image/
[28] https://www.knmi.nl/knowledge and data centre/background/knmi-23 climate scenarios
[29] https://iplo.nl/theme/water/application models/water management models/
[30] https://www.deltares.nl/software-en-data/products

as models for performing calculations for heat stress and drought. The results of the computation models for climate adaptation for the whole of the Netherlands were also made available in the Climate Impact Atlas .[31] Municipalities can use this data to carry out climate stress tests. Of course, the spatial context in which climate change occurs is also changing and space use models are being used to capture those changing circumstances for the whole country, as has recently been done for the Delta Scenarios (Claassens et al., 2023). The spatial use patterns from these model simulations are the input for hydrological effect determinations.

Mobility and transport models – also known as traffic models – help to manage the ever-growing need for the movement of people and goods. Mobility and travel have a major impact on the accessibility, quality of life and sustainability of the physical environment. Computation models provide insight into future transport flows and movements and their distribution between the different types of transport (modalities), such as by bicycle, car or public transport. The models have many applications, such as gaining insight into the advantages and disadvantages of new infrastructure or expanding existing infrastructure. For this purpose, it is calculated how many vehicles drive on which roads and what the effects of mobility alternatives are, for example for traffic intensity, travel times, noise pollution, air pollution and nature. These forecasts serve as input for cost-benefit analyses and environmental impact assessments.

Various traffic and transport models are used in the Netherlands. Examples of national models are the National Model System[32] (LMS) and the Dutch Regional Model[33] (NRM). There are four regional models of the NRM in use for more detailed applications per part of the country (NRM-North, -East, -South and -West. With these models, long-term forecasts can be made and the effects of policy investigated. For example, the effect of a lane; What does that mean for a traffic jam? Does the traffic jam resolve or not? Is there extra traffic due to the widening and what does that mean for the air quality or the amount of noise? Provinces and municipalities usually use regional or local models to make more precise traffic forecasts for their area, such as VENOM[34] and V-MRDH[35]. In addition, consultancies are active, supporting traffic studies with their own models such as OmniTRANS[36] and Urban Strategy[37].

Energy models help to explore, substantiate and justify the choices regarding energy use and the energy transition. Which sustainable solutions do you use within your municipality, region or province? Do you want to reduce CO2 emissions? Want to become energy neutral? What options do you have to reach your goals? Various computation models are used to answer such questions and to draw up regional energy strategies, energy transition visions, heat and system studies. This allows the contributions and effects of solutions such as the electrification of mobility, a sustainable heat network or a solar park to be explored. You can also zoom in on the built environment: What is a cost-effective solution for a particular neighborhood? And then comes the thinking about implementation, such as what is a smart design of a heat network. Each step involves a different energy model. An example is the Energy Transition Model,[38]which helps municipalities, provinces and grid operators to answer questions such as: What happens to the energy system if you opt for a certain sustainable energy solution? How do supply and demand connect?

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[31] https://climateadaptatienederland.nl/tools/overview/climateeffectatlas/

[32] https://www.rijkswaterstaat.nl/wegen/wegbeheer/bouw-wegen/nederlands-regional-model-nrm-en-landelijk-model-system-lms

[33] https://www.rijkswaterstaat.nl/wegen/wegbeheer/bouw-wegen/nederlands-regional-model-nrm-en-landelijk-model-system-lms

[34] https://transportregio.nl/venom

[35] https://mrdh.nl/project/traffic model

[36] https://www.goudappel.nl/nl/expertises/data-and-it solutions/traffic modelling software-omnitrans-expert

[37] https://www.scenexus.com/urban-strategy/

[38] https://energytransitionmodel.com

Demographic and more specific *market models* focus on making forecasts about the growth and composition of the population and related to the housing stock, housing needs and housing shortage. An example of a national model that makes forecasts at municipal and neighborhood level for population, households and housing stock is Primos[39]. In addition, the model makes statements about the estimated housing shortage. PEARL[40] is another demographic forecasting model with a housing module, in use at the PBL. The government uses forecasts from these types of models, for example, to determine how many houses need to be built and in which locations. But also for the planning of public facilities such as (primary) schools or the supply of energy, it is necessary to have a good indication of the spatial distribution of different demographic groups.

Nature models include computation models for ecology, nature, landscape and biodiversity. The nature models are, for example, about the suitability of habitats for specific plants and animal species, or the development of forest areas under different management conditions. Such models are often also useful for determining the effects of climate change. An example of an ecological model is the PBL's[41] MetaNaturePlanner, which maps the sensitivity of plant and animal species to changes in the size and quality of a habitat through type management, environmental and water conditions. The Nature Technical Model[42] has been developed to help assess whether ecological restoration contributes to improved conditions for vegetation. DIMO[43] is a plant dispersion model to investigate the possibilities for plant distribution and migration.

Agricultural models mainly focus on the production improvement of agricultural activities such as livestock farming, greenhouse horticulture, open and covered cultivation. But these models can also provide insight into the additional effects of agricultural production on the physical environment, in particular agricultural emissions and emissions. For production improvement, computation models are available such as SWAP[44], which simulates the transport of flow and transport processes of water, dissolved substances and heat in unsaturated/saturated soils at field level during growing seasons and for long periods. NUFER quantifies[45] nitrogen and phosphorus flows in food chains and calculates the efficiency of nutrient use. Emissions of ammonia, smell and particulate matter, such as OPS[46] for nitrogen emissions, V-Stacks for[47] smell and ISL3a[48] for particulate matter, are the subject of extensive legislation for livestock farms in particular. In addition, computation models are also available for the use of pesticides[49] in agriculture.

Economic models are computation models that are aimed at calculating economic characteristics of the physical environment. These may include macroeconomic aspects of society as a whole, such as taxation, social security and labour market, public finances and purchasing power and labour costs. More specifically for the physical environment, economic computation models are used for (social) cost-benefit analyses, failure cost analysis and demand-supply analyses for the energy sector, among others.

Health models describe the factors in the physical environment that contribute to quality of life and health. To improve people's health, an environment that enables healthy behavior is an important

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[39] https://primos.datawonen.nl/jive

[40] https://www.pbl.nl/models/pearl-projecting-population-events-at-regional-level

[41] https://www.pbl.nl/models/meta-natureplanner-model-for-nature-policy-mnp

[42] https://www.wur.nl/en/show/nature-technical-model-ntm.htm

[43] https://www.wur.nl/en/show/plantsdispersionmodel-dimo.htm

[44] https://swap.wur.nl/

[45] https://www.wur.nl/en/research-results/chair-groups/environmental-sciences/earth-systems-and-global-change-group/research/water-quality/nufer.htm

[46] https://www.rivm.nl/operational priority substances model

[47] https://www.infomil.nl/topics/agriculture/smell/model-v-stacks/

[48] https://www.infomil.nl/topics/air-water/air quality/stroke/isl3a/

[49] https://www.wur.nl/en/research results/research institutes/environmental-research/facilities-tools/software-en-models.htm

condition in addition to attention to behavior and lifestyle. It involves different levels in the physical environment that affect: from the micro- (close to the individual), meso- (community, e.g. school, neighborhood or municipality) to macro level (society). For example, from a national exercise campaign, a municipality decides to build a sports field, so that people move more.

Sustainability models are used as a measurement system for sustainable development. They make the concept of sustainability measurable. In these models, the effects of economic growth are calculated for the broad prosperity for now, but also for later and elsewhere in the world. This is also called the model for Broad Prosperity, as sustainability is increasingly called. The best-known example of a sustainability model is the Wide Prosperity Monitor.[50] This sustainability model gives a picture of the sustainability of Dutch society. The monitor shows in which areas sustainability is doing well and what concerns are about. The monitor presents a collection of factors (so-called indicators), which describes sustainable development well.

Space use models are examples of integral models that are used, among other things, to be able to translate future sectoral space claims into an integrated spatial vision for the future. Various (socio-economic) future scenarios are often used to explore the bandwidth of possible spatial futures. Models such as Space Scanner[51] are used to translate the narratives of those scenarios into patterns of space use(Koomen et al., 2024). The model integrates outcomes from a variety of sectoral models (such as regional projections for housing stock expansion or job numbers, e.g. from the Tigris XL model[52]) into detailed maps of future space use. A recent example of such a scenario study concerns the spatial exploration of the design of the Netherlands in 2050 by the Netherlands Environmental Assessment Agency(Hamers et al., 2023). The model is also able to visualize more trend developments (Kuiper et al., 2023) or to explore the costs and benefits of changes in water management and the potential impact on agricultural land use(Van den Born et al., 2016). Incidentally, such exploratory scenario studies can also be drawn up in a more design-oriented way, as in the scenarios for Dutch agriculture in 2050 of Wageningen University (Lesschen et al., 2020).

Space scanner

The Space Scanner computation model was developed by the Netherlands Environmental Assessment Agency (PBL) to translate future space claims into integrated spatial future images of the Netherlands. The model uses various socio-economic future scenarios to explore possible spatial developments and determines the space needs of different sectors per region.

The model stems from the collaboration of a number of institutes. Space scanner is developed with the open source software framework GeoDMS for (spatial) modeling of the company ObjectVision. In recent decades, the model has been widely used for various spatial planning projects in the Netherlands, mainly by the PBL and its predecessors. The Vrije Universiteit Amsterdam (VU) conducts scientific research for the methodological development and calibration of the model, working closely with the PBL and ObjectVision. The collaboration between these parties ensures an integration of academic expertise, policy analysis and technical support, resulting in a powerful computational tool for spatial planning and policy making in the Netherlands.

3.7 Conclusion

There is a huge wealth of computation models in the Netherlands. These models all have their own function, model approach and application domain. Many models often even have multiple functions, apply different approaches and therefore have different application domains. This can be

[50] See https://www.youtube.com/watch?v=fZSq1UhnEC4

[51] https://spinlab.vu.nl/research/spatial-analysis-modelling/land-use-scanner-model/

[52] https://www.pbl.nl/publications/to-a-new-tigris-xl

clearly illustrated by the Green Benefit Planner,[53] the most important features of which are shown in Figure 14.

This calculation tool was developed by RIVM to provide insight into the social and financial benefits of greening in cities. The aim is to show that green is not a cost, but rather adds value, both economically and for the well-being of residents. Green reduces heat stress, provides shade, and helps reduce waterlogging. Residents of green neighborhoods also feel healthier and make less use of care. New greenery can generate social benefits of €1 to €10 per square meter per year, depending on the location. The computation model is based on the Natural Capital Model (Remme et al., 2017), which calculates ecosystem services and their monetary value. The model uses data from basic registrations such as BAG, BRT, WOZ and CBS data. The input and output for the model are integrated into 3D environments of consultancies such as Tygron, ESRI and Strategis, which translate the model output into visualizations for decision-makers and stakeholders. The model is thus included in the digital twins of cities such as Zwolle and Amersfoort to make the benefits and effects of greening visible in the redevelopment of districts and station locations and the design of new residential areas. The Green Benefit Planner performs various functions. The green benefit planner can serve as a prescriptive model with which to indicate how to act in order to meet certain objectives. This allows alternative options for greening to be calculated to determine whether they meet specific objectives. The relationships between the included variables in the green benefit planner and the underlying Natural Capital Model are linear and it applies different approaches. This gives the model a wide range of application domains. The green benefit planner is also a nature model, because it is based on natural capital. Natural capital consists of services and supplies that nature provides to us. These ecosystem services and supplies have different functions, such as food production or cooling in the city. With input from the Natural Capital model, the planner calculates the effects of interventions in the physical environment, such as greening or petrification, housing construction, or construction of infrastructure. The results of the green benefit planner are used in different model calculations: Air quality – particulate matter (environmental model), CO2 emissions (climate model), rainwater drainage (water model), sports and exercise, general practitioner and hospital visit (health model) and housing value, water treatment costs, healthcare costs, sick leave (economic model).

[53]https://atlasnaturalcapital.nl/green-benefit-planner

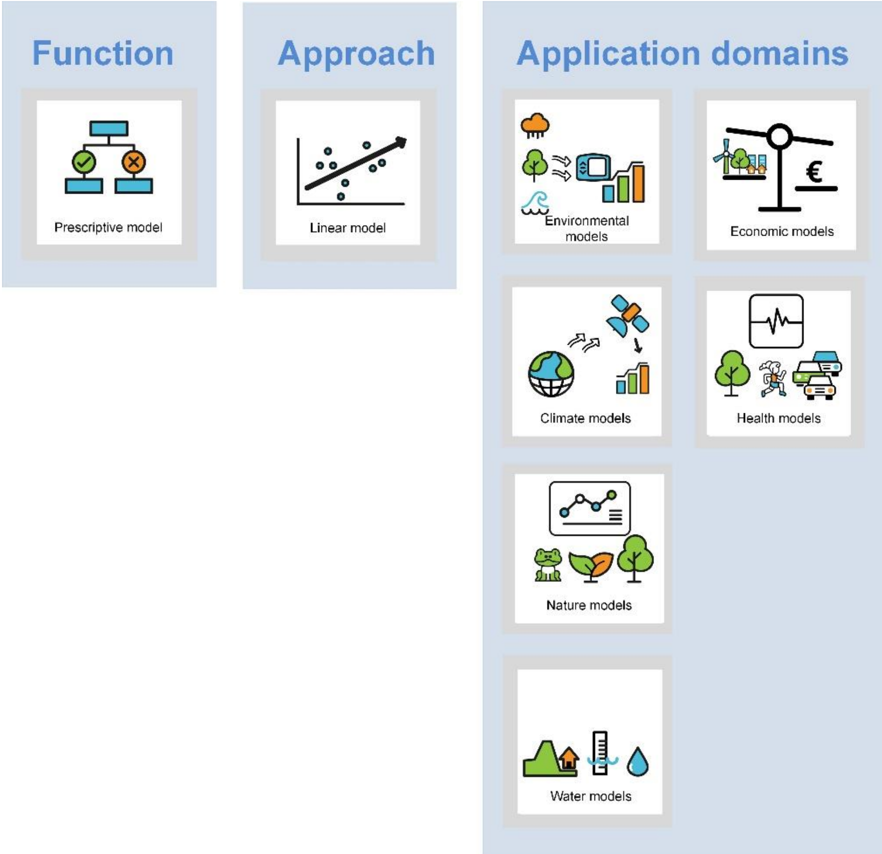

Figure 14 - The green benefit planner classified by function, model approach and application domain.

This overview is valuable because it shows how diverse, extensive and specialized the landscape of computation models in the Netherlands is. By combining the different functions, approaches and application domains, policymakers, researchers and advisors can better understand which model is suitable for a specific situation. This helps in choosing the right model to analyze complex issues around the environment, economy, health and climate and to develop solutions that are socially and economically valuable.

At the same time, it makes clear how complex it is to have these models work well together and effectively incorporate them into digital twins. Different functions, approaches and application domains make integration challenging, which requires careful coordination and technical solutions. In the next chapter, we will therefore go deeper into what is needed to make these models work better together and how interoperability of computation models and digital twins can be shaped.

4. Interoperability of computation models

4.1 The EU Interoperability Framework

Digital twins often use a variety of computation models to simulate behavior, make predictions, or support decisions. For example, an urban digital twin contains and integrates computation models for various purposes, such as traffic movements to simulate congestion, calculate energy consumption and for calculating the environmental impact such as air quality and noise. These computation models need to process and share data, such as weather forecasts or population data, in order to create an integrated picture. Interoperability refers to the ability of different data sources, computation models, systems and software components within a digital twin to work together effectively, exchange data and function integrated as a whole. Interoperability means that different systems, computation models or tools are able to share data and exchange this data in a standardized and understandable way. In the context of digital twins, this means that computation models from different disciplines, software environments or technologies must communicate and collaborate with each other without any problems.

Interoperability is a fundamental feature for the success and reliability of computation models within digital twins. It ensures that the components of the digital twins – data, computation models and visualizations – can work together as a coherent whole.

Because digital twins are often used in complex applications such as urban planning, healthcare, industrial processes and climate modelling, it is a requirement that computation models from different domains function together. Interoperability ensures that these models work together coherently and efficiently, which is crucial for accurate and reliable simulations. But clear agreements will be made for this, whereby the agreements are both organizational, legal, semantic and also technical in nature.

On the 18th of November 2022, the European Commission published the proposal for the Interoperable Europe Act[54]. The Commission sees the regulation of international interoperability of public services as a fundamental precondition for further developing and perfecting the digital single market[55]. Better international interoperability in the public sector creates innovation opportunities, enables better planning, for example in crisis situations, and strengthens the EU's technological sovereignty. The Regulation has three objectives:

1. Ensure a consistent, people-centered European approach to interoperability, from policy-making to policy implementation;
2. Establish an interoperability governance structure, which should enable public administrations at all levels and in all sectors, as well as private stakeholders, to work together with a clear mandate to agree on shared interoperability solutions (e.g. frameworks, open specifications, open standards, applications or directives);
3. Together, create an ecosystem of public sector interoperability solutions in the EU, so that public administrations (at all levels in the EU) and other stakeholders can contribute to and reuse such solutions, and jointly innovate and create public value.

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[54] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32024R0903

[55] The text in this section is largely from: https://docs.geostandarden.nl/eu/handreiking-EU-information/#interoperable-europe-act. The complete regulation can be found here: https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=CELEX:32024R0903

The renewal, creation or acquisition of information and network systems should take into account European interoperability requirements, as set out in the European Interoperability Framework (EIF) since 2010.[56] In the Netherlands, compliance with the EIF is anchored in NORA.

The Interoperable Europe Regulation establishes a general and prescriptive framework for interoperability of network and information systems, which are used to provide and manage public services in the European Union. The Regulation applies to all public institutions providing or operating information systems or networks for the electronic provision or management of public services. It sets out measures to strengthen the cross-border interoperability of information and network systems, i.e. the international connection and exchange of public services in chains between Member States. The proposal distinguishes between four aspects of interoperability (see also Figure 15):

1. Legal interoperability; legal frameworks, which affect interoperability;
2. Organizational interoperability related to coordination between organizations;
3. Semantic interoperability, which captures the meaning and format of data exchanged;
4. Technical interoperability for technical aspects of data sharing and data exchange.

Figure 15 - The EU Interoperability Framework[57].

The Commission argues that a high level of public sector interoperability is needed in all these areas. Interoperability solutions are all technical specifications (such as a standard, conceptual framework, guidelines, applications and, where applicable, documented source code) that describe legal, organizational, semantic or technical requirements for an information system to enhance cross-border interoperability.

In the following sections, we use the above classification into four forms of interoperability to classify the main findings from this study. Here we discuss the points of attention and developments, which were recorded during the execution of this study from the interviews with Dutch experts and from their suggested sources (for desk research). This inventory mainly seeks to collect recommendations to enable interoperability by aligning with recent legal, organizational, semantic and technological developments. In addition, in the final paragraphs we pay attention to

[56] https://interoperable-europe.ec.europa.eu/collection/nifo-national-interoperability-framework-observatory/european-interoperability-framework-detail

[57] Free to: https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf

some aspects of use that were discussed in the discussions. These mainly concern how modellers and model users can contribute to the responsible use of their models.

The text in this chapter is enriched with blue framework texts in which we give inspiring practical examples of ongoing projects and systems. We also mention a number of areas of focus for innovation and research. All these examples were mentioned in the interviews by the experts for illustration and indicate how we can achieve an effective link between computation models and digital twins.

4.2 Legal Interoperability

The legal frameworks for computation models are determined by regulation at national and European level. We therefore discuss these frameworks in relation to some important laws and regulations. Legal interoperability for the use of computation models in digital twins refers to the extent to which legal and regulatory frameworks are consistent and compatible so that computation models (and related data) can be lawfully shared, integrated and used within and between organizations. The legal interoperability of computation models also ensures that digital twins can be used legally safely and effectively. The legal aspects of interoperability for computation models include aspects such as licenses and property rights, liability and contractual agreements on the use of the computation models. But computation models are also laid down in general regulations (e.g. the European AI Regulation) and specific domain legislation (e.g. the Dutch Environment and Planning Act). Legal agreements have also been made on (the use of) computation models.

4.2.1 Computation models in Dutch legislation

In the Netherlands, computation models for the physical environment are sometimes included in legislation to standardize complex calculations or analyses and to support policy. This is done in accordance with clear guidelines and procedures to ensure the reliability, transparency and applicability of the computation models. The application of a computation model is then made mandatory for certain calculations, such as in environmental law. The law refers to a specific computation model and/or an annex describing the computation model. Computation models are therefore explicitly mentioned in laws, general administrative measures or ministerial regulations. And in some cases, a technical document or manual is included in which the operation and application of the computation model is explained in detail, such as for noise calculations in the physical living environment (see box).

The computation models are assessed for robustness, reliability and validation before being incorporated into legislation. They are regularly evaluated and adapted to new scientific insights or policy goals. The computation models should be publicly available and based on scientific insights. This increases accountability and support among stakeholders. This is because computation models sometimes also serve as a basis for checking and complying with laws and regulations; public authorities and licensing authorities can use the computation models to determine whether certain standards or requirements are met.

Sound models in the environmental law

The use of computation models in noise calculations for the Environmental Act aims to assess whether activities comply with legal standards for noise pollution, as laid down in the Environmental Act. The noise models support permitting, spatial planning and infrastructure design. The noise models are laid down in the law in the form of calculation and measurement regulations and are used to model noise emissions from roads, railways and industrial activities. The sound models calculate noise levels based on inputs such as traffic intensity, vehicle types, speed and environmental factors (e.g. soil absorption and buildings). The results from noise models are legally binding when granting a permit or drawing up an environmental plan. Agreements have been made on the quality of the sound models; the sound models must comply with legal requirements for accuracy, validation and transparency, which are laid down in the Decree on Quality of the Living Environment[58] and the Environmental Regulation[59].

4.2.2 The European Artificial Intelligence Regulation

As of the 1st of August 2024, the Artificial Intelligence Regulation has entered into force from the EU. The use of AI by public authorities will have to comply with specific requirements from its entry into force, depending on the level of risk of its application. AI models are analyzed based on their impact on safety, health and fundamental rights, such as privacy and non-discrimination. Risk management is central to this. AI systems should be typed and regulated based on a risk-based approach: from unacceptable risk, high risk, limited risk to minimal risk.

High-risk models will have to meet strict conditions for design, implementation and monitoring. For this purpose, a CE marking for high-risk AI systems is established. This is a certification that indicates that an AI system meets the standards and requirements of the European AI Regulation and meets the legal requirements in terms of safety, reliability, transparency and ethics. High-risk AI systems such as those used in critical sectors such as healthcare, law enforcement, transport or education are therefore subject to strict rules and obligations under the AI Regulation.

In addition, developers and users of AI systems should ensure the transparency, traceability and explainability of AI systems, including by testing, describing and ensuring quality assurance of AI systems. Users of AI systems should therefore be informed about how models work, what data is used and how the output was created. Agreements and mechanisms for monitoring and auditing AI algorithms will also need to be implemented to ensure that they continue to operate safely and comply with regulations. This requires, among other things, a description of the tests carried out to ensure reliability and accuracy. In addition, national supervisory authorities and a European AI Board should be established to ensure compliance.

According to the European AI Act, an AI system is defined as ‘a system that makes intelligent or autonomous decisions or recommendations based on data, using one or more AI techniques.’ [60] In the context of the AI Act, an AI algorithm or AI system not only works on the basis of pre-programmed rules, but can learn and adapt itself to new data. This minimizes or eliminates human intervention and is what typically sets AI algorithms apart from traditional algorithms, computation models, and systems. These are advanced algorithms that are able to perform tasks independently and are known as machine learning, deep learning, pattern recognition or natural language processing.

The EU is also working on a European AI database recording the high-risk AI systems used in the EU. This will support monitoring and verification of compliance with the AI Regulation by regulatory

[58] https://wetten.overheid.nl/BWBR0041313/2024-12-21

[59] https://wetten.overheid.nl/BWBR0045528/2025-01-01

[60] https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=OJ%3AL_202401689

bodies and verify that AI systems meet the required standards in terms of safety, ethics and transparency.

4.2.3 The Dutch Algorithm Register

The Dutch algorithm register[61] is an answer to the question of more transparency about the use of algorithms by the Dutch government as laid down in various reports, chamber motions and opinions (Ministry of BZK, 2022). In doing so, an algorithm is described quite generally as '...a set of rules and instructions that a computer automatically follows when making calculations to solve a problem or answer a question' (Court of Auditors General, 2022). This description is quite broad and includes more than just AI models. That is why the Dutch algorithm register focuses on registering high-risk AI systems and impactful algorithms. In any case, these are:

- AI systems, which are designated as high-risk by the European (Advanced AI). These are algorithms that know elements of autonomy and are usually (partially) self-learning algorithms. The AI system should also fall within one of the scopes of Annex III of the AI Act[62]. Think of areas such as biometrics, critical infrastructure and employment.;
- Information about algorithms that have a direct impact on those involved. For example, they contribute to a decision that affects someone's rights, someone's legal status or their rights under a contract. Think about: imposing a fine or granting or refusing a subsidy.

In addition, there are a number of other reasons for fully publishing algorithms, for example when algorithms receive a lot of social attention. However, there are also reasons not to publish all the information about an algorithm, for example when an algorithm is used for detection. Ideally, the government then publishes the part of the information about the algorithm that can be published. A separate guide has been[63] developed for selecting algorithms for publication in the algorithm register. Also for describing the algorithms, a publication standard has[64] been developed consisting of a set of information elements (metadata) about the algorithms. With the Dutch algorithm register, the Dutch government is looking for a connection to the European AI Act so that it becomes easier for governments with a high-risk AI system, which are in the Dutch Algorithm Register, to comply with this European obligation. Not all descriptions of algorithms in the Dutch Algorithm Register are about high-risk AI systems. There are also non-self-learning algorithms and/or algorithms with a lower risk in the registry, which are referred to as impactful and other algorithms.

In addition to an algorithm registry, the AI Management Toolkit[65] (AMT) is being developed to improve the transparency and governance of algorithms throughout their life cycle. AMT generates standardized reports on algorithms, including technical details and regulatory reviews, from development to deployment and use. This promotes accountability, supervision and cooperation, and is in line with requirements from the Dutch Algorithm Framework.

4.2.4 Computation model register for digital twins

Very closely related to the algorithm register is a model register or register of computation models, which was mentioned several times in the interviews for this exploration. Such a register can contribute to transparency about the functioning of the model and to the assessment of risks of model application in relation to laws and regulations such as the algorithm register. In doing so, it can help ensure consistency and reliability in the use of computation models, the flow of model management lines and the reuse of computation models. Such a register provides a central location

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61 https://algorithms.overheid.nl/en

62 For more information on the risk classification, see the AI Act itself at https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=CELEX:32024R1689.

63 https://aienalgoritmes.pleio.nl/attachment/entity/f1a35292-7ea6-4e47-93fa-b3358e9ab2e0

64 https://aienalgoritmes.pleio.nl/wiki/view/2bcdf820-ce62-4249-95f7-d1a13fb6e1c9/handleiding-publicatiestandaard

65 https://minbzk.github.io/ai-validation/

where all stakeholders (governments, companies, academic institutions) gain insight into the models used, how they work, and what their limitations are. A computation model register can record who is responsible for a computation model and how it has been developed. It can be a mechanism for finding computation models and keeping track of updates, changes, or new versions of computation models, so that users always have access to the most reliable and relevant version. A register improves the reuse of computation models for other applications and allows comparison of computation models from different suppliers (location).

Examples of such computation model registers are, for example, the Model Gallery[66] of Wageningen University & Research, the overview of models used by PBL[67] on their website and the Modelling Inventory and Knowledge Management System (MIDAS[68]) of the European Commission. These registers shall contain, among others, information on:

- What the model does, for what purposes it is used, and the scope of the application;
- Metadata on the input and output of the model used, the type of data, and the algorithms applied;
- Quality control and validation: data on the validation of the model, such as quality assurance methods and testing;
- Owners and managers: information on who developed, maintained and is responsible for the outcomes of the model;
- Agreements on the sharing of the computation model and, for example, the conditions for re-use (licensing conditions);
- Information about the different versions of the model, including updates, changes and validation of results.

A computation model register thus performs a similar function to an algorithm register and also contributes to transparency and to reducing the risk of improper or irresponsible use.

4.2.5 Origin and traceability

Another important aspect of computation models that was also frequently highlighted in the interviews is attention to the standardized recording of *origin* and *traceability* of the way in which computation models are applied. These are two important aspects to be able to comply with legislation and legal requirements in relation to transparency for decision-making (see also box).

Origin or provenance refers to capturing the history of computation models and their data. This involves documenting their origin and processing, and the processes that have been applied for this purpose. In applications in the public sector, where decisions can have a significant impact on (vulnerable) people, insight into the origin of data ensures that policy is based on accurate and reliable information. In doing so, transparency about the model and data origin contributes to confidence in model application and the origin of the input data used, ensuring data integrity and facilitating regulatory compliance.

Traceability includes the ability to track the use of computation models and data throughout their life cycle. For example, it can be checked how computation models are applied, any changes can be identified and insight can be obtained into the data flows between different calculation systems. In digital twins, traceability ensures that all components function as intended and that any problems can be quickly identified and addressed. For applications in the public sector, this means that services relying on digital twins can maintain high standards of quality and reliability.

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66 https://www.wur.nl/en/research-results/knowledge-online-research-projects-lvvn/knowledge-base-research/kb-projects-current-2019-2024/wageningen-research-modeling-group-kb-33.htm
67 https://www.pbl.nl/models
68 https://web.jrc.ec.europa.eu/policy-model-inventory/

Standard for transparency in decision-making

It is important that the government provides accountability and transparency to citizens and businesses about its actions. Citizens and businesses need to know what data is used and how decisions are made. Not only personal data, but also data about objects in the physical environment are used. A standard for recording and justifying the processing of personal data is being developed.[69] This project[70] aims to expand this standard so that it can also be applied in the physical environment. In this way, the entire government can be held accountable in a uniform, consistent and easy-to-implement manner. Initiators of the project are the Ministry of the Interior and the Geonovum Foundation.

4.3 Organizational interoperability

Organizational interoperability in the use of computation models and digital twins refers to the ability of different organizations to effectively collaborate around the use of computation models and digital twins. This can pose challenges in terms of policy, governance, collaborations between organizations and business processes (such as revenue models). To this end, both public, private and knowledge organizations must make agreements with each other and exchange information. Addressing these organizational aspects contributes to the successful implementation and exploitation of computation models and digital twins within and between organizations. This concerns various aspects on which agreements must be made, such as agreements about the management (models), the cooperation between public, private and knowledge organizations, the agreements and guidelines about processes, quality and revenue models. In short, developing common policy frameworks and governance structures, which facilitate the sharing and joint use of computation models in digital twins.

The sharing of data and computation models benefits from strong partnerships between various organizations, such as government institutions, research institutes and private parties. Setting up platforms for the exchange of computation models and data can facilitate this cooperation, promote transparency and contribute to the necessary trust between stakeholders to effectively share data and models. This sharing requires shared objectives, mutual understanding of each other's roles and responsibilities and clear agreements on, for example, responsibilities and procedures for data management and exchange.

Agreements on how common standards and guidelines for the use of computation models and digital twins are used and enforced are also crucial. This ensures consistent and efficient implementation at national, regional and local level. In addition, the integration of computation models and digital twins into the business processes of organizations is an evident aspect of organizational interoperability. It is important to also harmonize business processes to ensure compatibility - smooth integration and application of computation models and digital twins - and effectiveness of the use of computation models and digital twins. This includes streamlining workflows, defining common procedures and implementing interoperable IT systems.

Finally, attention to developing sustainable revenue models (and licensing computation models) is also essential for the adoption of uniform computation models in digital twins. It is important to clarify the value proposition of using computation models in digital twins and communicate it to all involved. Digital twins offer new opportunities and markets for existing computation modeling services and the development of new services, such as data analysis services and the creation of new products based on insights obtained from digital twins.

In the sub-paragraphs below, we will elaborate on some examples that illustrate how the organizational interoperability of computation models and digital twins is already achieved in

[69] https://logius-standaarden.github.io/logboek-dataverwerkingen/

[70] https://geonovum.github.io/logbook-dataprocessing-for-objects

practice. These examples relate to collaborations and revenue models that have emerged in the discussions with experts in this exploration.

4.3.1 Organizing cooperation

In the discussions, various partnerships and communities of practice were mentioned, in which Dutch organizations at different levels (from international to local) collaborate on the development and use of computation models and digital twins.

International cooperation - Open Modeling Foundation

The Open Modeling Foundation (OMF) is an international open science community dedicated to advancing the next generation of computation models for human and natural systems. It is an alliance of modelling organizations, which jointly develop and manage standards and best practices for various communities of modellers, in which some Dutch organizations such as WUR and Deltares also participate. OMF is an active organization, which regularly organizes meetings and workshops to promote the development of modelling standards. Within the OMF, a Standards Working Group is active, which plays a crucial role in the development and implementation of common standards. Their aim is to promote cooperation and transparent knowledge exchange by adopting uniform guidelines, which improve the interoperability and quality of models (Barton et al. 2022a). For the Dutch parties, participation has the advantage that they can integrate OMF standards and best practices into national projects. This leads to better collaboration between Dutch researchers and international communities and can increase the quality and reproducibility of models. At OMF, the focus is currently on properly describing computation models and aspects of semantic interoperability rather than technical[71]interoperability.

National Models and Data Centre

The National Models and Data Centre for the Living Environment (NMDC) is a collaboration between various Dutch knowledge institutes, including the KNMI, RIVM, PBL, Deltares, Wageningen Research and TNO. The NMDC aims to combine knowledge in the field of the living environment and the environment by sharing each other's knowledge and expertise, aligning models, data and infrastructure, and stimulating joint use.

This integrated approach prevents fragmentation of research capacity and promotes a safe and sustainable living environment. Participants agreed on the development and use of computation models, including:

- The joint development and maintenance of models and data infrastructures;
- Promoting the interoperability of models and data;
- Ensuring the quality and reliability of models and data; and
- Encouraging open access to data and models, while respecting legal and ethical frameworks.

Cooperation between knowledge institutions – Digilab Applied knowledge

The Dutch Applied Research Institutes (Deltares, MARIN, NLR, TNO and WUR, united in the TO2 federation) started at the beginning of 2024 with the Digilab Applied knowledge and with the sharing of data and computational capacity, so that the knowledge institutes can use each other's analysis and modelling techniques. To strengthen their innovative power, these TO2 organizations together with a number of leading national knowledge institutions (such as RIVM and PBL) invest in a digital infrastructure: the DigiLab Applied Knowledge (DigiLab).[72] This is a digital facility where data, models and computing capacity can be shared. In this way, the knowledge institutes can work together even better and the Digilab, as an innovative ecosystem, enables the knowledge institutes to find solutions to complex research issues. Whether it concerns climate change, energy

[71] More about the Open Modeling Foundation: https://www.youtube.com/watch?v=oG9_Y2Kfl5Y&t=1127s

[72] https://to2-federatie.nl/article/to2-digilab-bundling-of-joint-mind/

transition and sustainability, nitrogen issues, health care and epidemics/pandemics, water and food security, or integral security issues, the societal challenges are large and complex. They change quickly and are difficult to predict. Cooperation between research institutes, knowledge institutes, other governments and industry is crucial to solve these issues. This collaboration is increasingly digital, making the need to be able to share and use each other's data and models increasingly urgent.

Finding answers to the complex research questions therefore benefits from a digital facility: a federated, digital infrastructure that provides access to this 'exploding' amount of data and models. In this facility, data and models are combined with computing power and modern visualization environments. A development that is made possible by increasingly powerful computers. It also supports the development of AI and creates insight using complex simulations and visualization in digital twins. Digital collaboration is complicated by the fact that parties want and have to maintain sovereignty over their data, algorithms, computation models. Often there is a willingness to make these components available subject to conditions, but not to fully transfer these components. In addition, fragmentation of data, algorithms and computation models causes a lack of reproducibility and transparency. The latter is crucial for the social acceptance of outcomes that are increasingly under pressure. Finally, any cooperation must take into account knowledge security and protection against digital threats. These aspects are the same for all institutions and require a common, scalable solution. The DigiLab removes these obstacles to digital collaboration and provides an ecosystem in which co-creation and joint use of data and models can take place safely, transparently and reproducibly.

In addition to the knowledge institutes, (semi) government organizations, educational institutions and the business community can also be connected to the Digilab in the long term. However, these parties also have the desire to keep control over their own data. This certainly applies, but not only, to market parties that play a crucial role in applied research. Such parties will not simply share data with others due to business or legal considerations. Similar strategic interests often apply to other parties, for example to keep a knowledge lead or to be the first to publish about new developments. Such considerations may conflict with the often mentioned willingness to cooperate. Digilab Applied knowledge wants to offer a solution, by making data and computation models available only under certain conditions and to specific groups. In this way, each party retains control over its own data. It is a virtual collaboration environment in which connected parties have flexible, efficient and secure access to each other's data, algorithms, models and computational capacity under the agreed conditions. A similar virtual collaboration environment is not yet available.

Domain-specific cooperation –Watercloud

The Watercloud initiative is a collaboration between Dutch water managers and knowledge institutions, including Rijkswaterstaat, the water boards, Deltares and the KNMI(Aalders et al., 2020). The goal of Watercloud is to promote collaboration in the field of water management by sharing data, models and computing power through a joint cloud environment. With this collaboration, the parties involved strive for an integrated approach to water management, using shared digital resources from the Dutch Hydrological Instruments (NHI) to better respond to challenges such as climate change and water safety. The main goals of Watercloud are:

- Facilitating access to up-to-date and reliable water data and computation models for all participating parties;
- Optimizing computational processes by using shared cloud resources, leading to cost savings and faster turnaround times;
- Stimulating joint development and implementation of new technologies and methods in water management.

A functional design for Watercloud was developed (Aalders et al., 2020) in 2021, with functionalities such as the NHI Modelcode selector, workflow support and post-processing. These applications are in line with the objectives of NHI and fulfil the first version of Watercloud.

Cooperation within one organization - Wageningen University and Research

Organizational interoperability for the development and use of computation models can also be a theme within organizations. This contributes to the more uniform development and use of computation models throughout the organization. This form of interoperability can be supported by guidelines and agreements. The WUR Guidelines on Model Management of Wageningen University & Research (WUR) are an example of this and provide a framework for the management of models within an organization (Vullings et al., 2024). These guidelines apply to all WUR employees involved in the development and use of computation models.[73] Within the WUR it has been agreed that computation models comply with some general rules, such as:

- Models should be managed as far as possible according to the FAIR (Findable, Accessible, Interoperable, Reusable) principles;
- The WUR Data Policy and the WUR Guidelines on Value Creation with Software & Data; and
- The Good Modelling Practice must be applied.

In order to implement these general rules, various agreements have been made, organizational changes have been initiated and concrete agreements have been made within these guidelines. The WUR Guidelines on Model Management mentions, (Vullings et al., 2024) among other things:

- Model developers are responsible for documenting their models, registering in the WUR Model Gallery, safely storing and versioning, and assessing model quality;
- All models must be registered in the WUR Model Gallery with full metadata. The metadata must be updated periodically (annually) and models with a certain quality status can, after approval, be made visible outside WUR;
- Supervisors must ensure that team members have adequate training, adhere to the guidelines and that there is a model manager within the team;
- Model managers provide first-line support in complying with the guidelines;
- The model coordinator supports the implementation and further development of the guidelines and leads the Wageningen Modelling Group;
- Models are classified on the basis of impact and are given a quality status (e.g. self-assessment, Status A, Status AA) where the frequency of quality checks varies based on the impact class of the model;
- Model auditors are trained colleagues who carry out quality assessments;
- The Wageningen Modelling Group reviews the guidelines every four years and coordinates the development and maintenance of the building blocks;
- Models must be stored securely and version management must be applied, depending on the impact class;
- Designs underlying publications must be kept for a minimum of 10 years; and
- The Dean of Research appoints a model coordinator to monitor compliance with the guidelines and reports to the Executive Board.

4.3.2 Earning models

Another recurring topic in the interviews concerned the revenue model for both public and private providers in the provision of (integrated) model services and the linking of computation models within digital twins. The use of computation models and digital twins is already being implemented in various ways, such as:

[73] The guidelines are also 'in line with the Dutch Code of Scientific Integrity and promote the scientific use of models, including sharing, reuse and verification, and help ensure WUR's (Vullings et al., 2024)reputation'.

- Subscription-based services, where providers give their users access to digital twins through a subscription model, including regular updates and support;
- Licensing for specific applications of certain models or functionalities within a digital twin;
- Providing predictive analyses, policy and impact reports based on integrated computation models, for example for traffic flows or environmental impacts, that support users in policy, planning and decision-making.

In order to apply computation models in the near future more modular and interoperable within digital twins, questions about revenue models will also need to be answered, such as:

- What is the optimal pricing?
- How can the value of these services be effectively determined for potential customers?
- How can licensing terms be drafted to ensure both flexibility for the customer and protection of intellectual property?
- Which computational functionalities are most valuable for different user groups?
- Which data sets are essential for accurate predictions?
- How can the accuracy and reliability of predictive models be guaranteed?

Exploring these revenue models and answering the associated research questions can help develop sustainable and valuable services for digital twins, with both public and private parties taking advantage of the opportunities offered by digital twins.

4.4 Semantic Interoperability

Semantic interoperability involves speaking a shared language to ensure that the meaning of data is consistent across different computation models. Semantic interoperability of computation models refers to the ability of different models and systems to exchange and interpret data with a shared meaning. This means that the data exchanged is understood in the same way by all systems involved, which is essential for collaboration between computation models and the generation of consistent and reliable results. Computation models use the same definitions, standards and ontologies for their data input, variables and data output. This avoids misunderstandings that may arise due to differences in terminology or interpretation. For example, if one model uses the term temperature in degrees Celsius and another in degrees Fahrenheit, without semantic alignment this can lead to inconsistent or erroneous results. Achieving semantic interoperability requires the establishment and implementation of common standards and agreements. This means:

- The use of uniform terminology by agreeing unambiguous terms and definitions prevents misinterpretations; and
- The development of standardized data models and ontologies, so that all involved models assign the same structure and meaning to data.

Several questions are relevant for the assessment of semantic interoperability of computation models. For example, can the model connect to another model (spatial and temporal synchronization)? And are the input and output variables described using a common vocabulary?

In order to achieve semantic interoperability, several aspects are important:

- Clarity and precision in definitions of parameters and variables (ontology);
- Inclusion of data items in metadata, such as scale (space and time), typical duration, limits (e.g. range of calibration data);
- Metadata and documentation related to interoperability;
- Compatibility of input and output variables.

With the help of sensitivity analyses or robustness tests, semantic interoperability can be tested to a certain extent. For example, one option is to replace input data with data from another source that describes the same variables and attributes. Think of two different satellite image-based input files that describe land cover to analyze whether a model achieves similar results. Such an exercise also has the advantage that the model is not recorded on one particular source.

Semantic interoperability is more than a technical exercise because it touches on the core of the computation models: what purpose they have, how certain concepts have been interpreted and conceptualized, which definitions have been applied, which data sources have been chosen for this, etc. Such choices can be discipline- or domain-specific which complicates exchange, because one discipline will have to accept the definition of the other (or vice versa). If the starting points of models are too different, a direct link can only be possible if one of the two models adjusts its starting points (e.g. input data, concept definition, aggregation method). In the discussions held, semantic interoperability was indirectly discussed as an important precondition for collaborative models. We will discuss this subject in more detail below.

Collaborative computation models

When simulating changes in the physical environment, complex interactions often play out between different socioeconomic and natural systems, which often have their own time and space scale. For example, climate change is an important driving force in many processes that take place on a much longer time scale and over much larger areas than most socio-economic changes. In choices about, for example, housing locations, this contradiction is clearly present. Attractive locations that municipalities would like to develop now may be unfavorable in the longer term from, for example, flood risk. Computation models describing both the physical and socio-economic domains will have to combine these different space and time scales. (Claassens et al., 2020) An important question then is how such models can work better together? This question also quickly arises when it comes to the interoperability of computation models. Models should first be designed as modular components so that specific functionalities can be replaced or improved without disrupting the entire system. By dividing models into small, independent modules that communicate via APIs, for example, the collaboration becomes easier.

Computation models typically operate at different scales and resolutions (geographical and/or temporal scales) and should be able to adapt their outputs to the requirements of other, linked models. This also means that standardized terminology and thus semantic alignment between models reduces differences in interpretation between models. Each model must be able to indicate:

- What data is used (input);
- What transformations or calculations have been performed;
- What results have been generated (output).

In the interviews, various preconditions and agreements were appointed for the cooperation between models when it comes to the data input, calculations and data output. For example, the data entered must meet certain quality standards, such as accuracy, completeness and timeliness. Input and output data for computation models should also be findable, accessible, interoperable and reusable (clearly described with metadata and documentation). There are specific aspects of FAIR making computation models as described below.

Computation models must have compatible data dimensions about, for example, units (Celsius vs. Fahrenheit), time scales (minutes vs. hours), or resolutions (meters vs. kilometers). Where these data dimensions conflict, a transformation intermediate layer should be used to translate or transform data. Each model must be documented in detail, including a description of the functions of the model, the data input and output requirements, and limitations of the model. Users must understand the limitations of collaborative computation models and that computation models require validation for the specific purpose for which they are deployed. If the limitations are too great, for example because one model defines a certain concept very differently, or represents it on a completely different spatial or time scale, it may prove impossible for models to work together. Interoperability is not an end in itself, but an aim to allow models to make use of each other's strengths where they make sense. In addition to semantic interoperability for input and output data, it is important that computation models also connect in their intended function, approach and conceptualization if they are used in the same digital twins. Especially if computation models have to do more than run a relay with each other (transmitting data), but also have to do this repeatedly or interactively with each other (output model A is input model B, output model B is input model A).

4.5 Technical interoperability

Technical interoperability involves the use of standardized technologies and protocols to enable the exchange of data between different computation models. Examples include APIs (Application Programming Interfaces), web services, and standardized file formats such as XML and JSON.

When it comes to technical interoperability of computation models and digital twins, various technical aspects are relevant to ensure that different computation models work seamlessly together within a digital twin. This includes at least technical coordination on the exchange of data (harmonizing data formats for input and output) and protocols for communication between models and possibly also their supplying data portals. Computation models must use the same data standards (data formats) to read data in and out, such as GeoJSON, CityGML, HDF5, NetCDF or cloud-native formats such as protobuf. Open protocols and Application Programming Interfaces (APIs), such as RESTful APIs or standardized OGC APIs, such as OGC API Features, 3D Tiles and OGC SensorThings API for IoT data, are used for communication between the models. Technical interoperability also increases productivity by simplifying a variety of modelling tasks. These tasks include:

- Running operational computation models in multiple different technological frameworks and/or on multiple technological platforms;
- Checking parameter values and behavior without recompiling code;
- Retrieving information about the current status of a model (including status variables);
- Interruption and continuation of model execution;
- Adjusting model variables and/or control parameters during a model run, for example to support data assimilation.
- Linking computation models (the model train) through standardized workflows;
- The modular provision of computation models with Notebooks and container technology;
- Being able to rely on GPUs quickly.

During the discussions, various aspects of technical interoperability were discussed. In the sections below, we elaborate on some important conditions and for technical interoperability and developments that make this possible.

4.5.1 Standards for technical operability of computation models

Interoperability standards are intended to integrate computation models, developed by a diverse (scientific) community, into modelling environments with multiple model components. Standardized interfaces, APIs and common ontologies are essential factors for achieving technical interoperability. In the discussions with the experts, several initiatives have been mentioned, which have worked worldwide on standardized interconnectors and interoperability standards, so that computation models applied in the physical environment can be more easily connected and thus become interlinkable (see Figure 16).

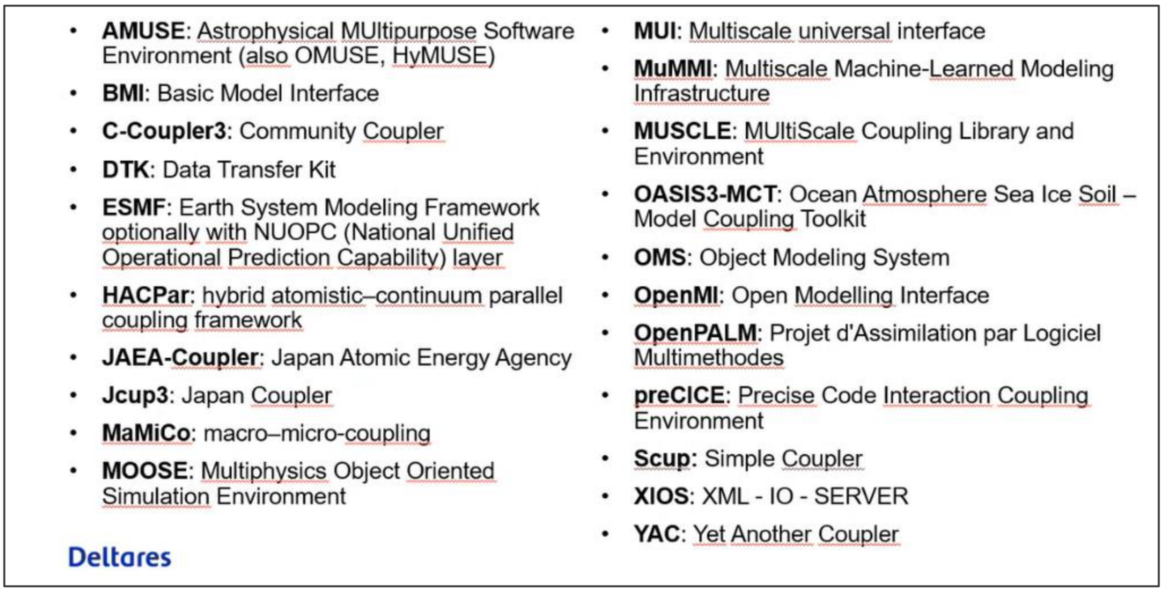

Figure 16 – Overview of global initiatives for linking computation models (freely based on Jagers, 2010).

Three of these initiatives actively involve Dutch parties and are briefly explained below[74]. Open Modelling Interface (OpenMI). Basic Modelling Interface (BMI) ,and OGC API Processes are standards, which aim to improve the interoperability and accessibility of models and processes across different scientific and technical domains. They have different approaches and purposes, but all three facilitate the linking and exchange of models between different systems and platforms. Below we discuss and compare the three initiatives with which experiences have been gained in different Dutch user environments.

Open Modelling Interface

The Open Modelling Interface (OpenMI) has been developed to enable the real-time exchange of data between different models during their execution. It is specially designed for linking models that need to exchange data while they are active. OpenMI is mainly used in hydrological and environmental modeling and serves to link models across different platforms and domains in a time-synchronized manner. Calculations are directly linked to each other and can exchange data in real time. This means that the models work together within a common implementation framework and exchange values at each time step. Synchronous communication between models is an important feature of OpenMI and allows data exchange during runtime between models, which means it can process real-time feedback between systems.

This close, synchronous, real-time linking makes the OpenMI interface relatively complex compared to BMI (see below). OpenMI was developed to link models from different parties without having to be open source. Although the standard received formal approval as an OGC standard, it is no longer used today, and BMI has partially taken over this role, with a focus on accessibility and platform independence. An important reason for this is to deal with technical interoperability between computation models, which run on different platforms, such as Windows and Linux. It is important

[74] Dutch parties are also involved in AMUSE (Leiden Observatory) and MUSCLE (UvA). However, these are initiatives with a (still) small user group, and therefore perhaps less relevant for the target group of this report. For more information on these initiatives: https://research-software-directory.org/software/amuse and https://research-software-directory.org/software/muscle3.

for both small and large-scale computation models that standards are widely applicable and also work with supercomputers.

Basic Model Interface

The Basic Model Interface (BMI) is a simpler, lightweight interface for model developers. The focus is on making models more accessible by providing a standard way to communicate with model input, output and states, without the need for real-time interaction. BMI is used to make models more accessible and easier to integrate into larger workflows. It provides a programmatic interface for interaction with models, allowing reuse in different contexts (e.g. in Python scripts or command-line interfaces). The Basic Model Interface (BMI) is an initiative developed by the Community Surface Dynamics Modeling System, an international community that works on the interoperability between different computer models in the context of earth sciences, such as geomorphology, hydrology, and coastal dynamics.

BMI focuses on providing a programmatic interface for a single model. It does not inherently provide the infrastructure for model-to-model communication, but provides a standard way to communicate with the model via function calls (retrieve/set model statuses, perform model steps). BMI has a direct model link like OpenMI, but models can be embedded in larger workflows. Data exchange is possible, but not in real-time or between multiple models. Simple get/set interface for inputs, outputs and time steps. This makes BMI easier to apply for modellers who don't need real-time interaction. Instead, it provides a standard way for a single model to expose its variables, making it more suitable for integration into workflows without complex synchronization. BMI is applied in projects, such as eWaterCycle (Hut *et. al.,* 2022) and MODFLOW (Hughes *et. al.,* 2022) to make models more accessible and reusable in different contexts, such as the water and environmental modelling community. In hydrology it is used, among other things, for linking different models related to water flow and transport of pollutants (see box).

Application Basic Model Interface - Deltares

Within Deltares, BMI is used to exchange data between hydrological models. Work is underway to integrate this interface into multiple projects, including hydrological applications for storm modeling and urban water management. Deltares is working internationally on BMI with the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) to deploy the interface to large-scale national models (Hughes *et. al.,* 2022). Since the end of 2017, Deltares has been working with the USGS on the MODFLOW source code. Deltares has been commissioned by the USGS to parallelize the open-source code of MODFLOW 6. The parallelization experiments show that significant accelerations in the calculation time can be achieved and that the MODFLOW 6 calculation core is in principle suitable for very large, high-resolution groundwater models. Another example of collaboration is the implementation of BMI in the MODFLOW 6 model code to enable linking to other models and other modelling domains. The BMI coupling has been successfully applied to the model for the unsaturated zone for the Netherlands, which is part of the Dutch Hydrological Instrumentarium (MODFlow 6)[75].

OGC API Processes

OGC API-Processes is a young standard of the Open Geospatial Consortium (OGC) and is the successor of the Web Processing Service (OGC WPS) standard. It is primarily used in the geo-information domain to perform geoprocessing tasks and models as web services and is gaining popularity due to its flexibility in cloud environments and distributed systems (see box). OGC API-Processes is a web-based RESTful standard designed to make geo-information processes available on the web. The primary goal is to provide remote access to processing tasks, whether simple or complex computation models, without the need to install or run the models locally. It is used to

[75] https://oss.deltares.nl/web/imod/-/new-modflow6-api-deltares-usgs

make a wide range of GIS-based processing tasks and computation models accessible via the web. OGC API Processes supports both synchronous and asynchronous communication, making it suitable for both real-time and batch processing.

This API standard uses HTTP-based communication to interact with computation models. Users make requests over the network to a server that executes the models or processes and returns the results via web services. This standard can handle different data formats (e.g. JSON, XML) and supports interaction with external data sources. This enables data exchange over the web, making it flexible for large-scale or distributed systems. The web-based, RESTful interface is relatively easy to use for a developer familiar with HTTP and REST APIs. This approach is well suited for modern web and cloud-based systems, allowing remote access to models and processes without local installation.

Practical example – Testbed OGC API-Processes

In this practical example, a testbed was[76] carried out of the use of OGC API-Processes to make some computation models in a digital twin accessible via a standardized API. In this example, a digital twin has been set up to simulate urban flood scenarios in severe rainfall. The concept supports policy making by offering easily scalable and reusable computation models, which have been demonstrated both in the municipalities of Almere and Rotterdam. OGC API Processes is used to make computation models, such as hydrological models that simulate flooding or visualize time series analyses) accessible as services within the digital twin. In the demonstration for the municipalities of Almere and Rotterdam, OGC API-Records (for the catalog function) and OGC API-Processes (for the computation models) were used to run simulations for flooding during heavy showers. Calculation modules are called upon to model waterlogging and drainage problems. Heat stress simulations are integrated via OGC API Processes to analyze urban heat effects.
The calculation tools are offered as separate building blocks, making them easy to reuse in different applications. The APIs are positioned as plug-and-play solutions, allowing users to seamlessly deploy computational tools in an ecosystem of digital twins. The APIs offer both a machine interface (e.g. JSON) and a human-friendly interface (e.g. HTML), so that they are accessible to various user groups.

The testbed was carried out as a collaboration of several companies (Future Insight, Tygron, Nelen Schuurmans, GeoCat, 52North and Imagem), the municipalities of Almere and Rotterdam and Geonovum.

4.5.2 Workflow management for computation models

Promoting collaboration and interoperability of computation models in digital twins requires workflows between computation models (European Commission, 2023; Grübel *et al.*, 2023). This is necessary to integrate and manage computation models, data and visualizations within a digital twin. Workflow management for computation models ensures the connection of computation models and their data flows through standardized interfaces (such as APIs). These standardized interfaces make it possible to set up workflows between computation models.

Workflow management tools ensure that models and data communicate seamlessly with each other. Workflow management also includes coordinating model interactions and process execution. Various technologies are used, such as workflow management tools and containerization technology (such as Docker). Workflow management tools such as Apache Airflow and Kepler coordinate the order of model execution, data transformations, and error handling (also called orchestration). Workflows such as OGC API Processes[77] can be easily adjusted to add new computation models or data streams.

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[76] https://www.geonovum.nl/themes/digital-twins

[77] http://www.opengis.net/doc/is/ogcapi-processes-3/0.0

Open Digital Twin Platform (ODTP)

Wageningen University & Research is collaborating on the Open Digital Twin Platform (ODTP).[78] This open-source framework facilitates the integration and collaboration of computation models within digital twins. ODTP uses standardized interfaces and protocols, allowing different computation models to work together effectively within a digital twin. A modular architecture allows users to easily add new components or replace existing ones, which promotes flexibility and scalability. The platform offers functionalities to ensure the reproducibility of workflows and the tracking of data flows. The main components of ODTP are:

1. Orchestrator: the core application that manages the execution of workflows;
2. Components: tools adapted to be compatible with ODTP, such as simulation and analysis tools;
3. Workflows: combinations of components in specific sequences to model and simulate complex processes;
4. Zoo: A collection of components available for use within the platform.

A prototype implementation of ODTP has been developed based on the agent-based simulation tool MATSim and the related pipeline eqasim for large-scale simulations. ODTP source code and documentation are available on GitHub where users can explore the tools and contribute to the further development of the platform. By providing this infrastructure, ODTP effectively supports workflow management and collaboration between computation models in digital twins, leading to improved integration, flexibility and reproducibility in complex simulation and modelling applications.

4.5.3 Growing data flows and scalable architectures

The discussions also frequently discuss the technology used to make different computation models work together so that they complement each other's functionality for complex task execution. Specific software connects computation models that use different technologies.

In the world of digital twins, the amount of available data is increasing rapidly. Sensors, computation models and user interactions in digital twins continuously generate new data. This continuous data flow offers opportunities for better analysis and decision-making, but also places increasing demands on the technical infrastructure and the performance to be delivered. With more data, not only the storage need grows, but above all the need to process this data quickly, reliably and in the right way. The digital twins must be able to react rapidly to changes and user interactions, for example for simulating traffic flows or calculating air quality or noise after a measure or intervention in the traffic system. This is often no longer about millions, but about billions of calculations. This requires a scalable architecture; a system that can easily grow with the increasing data volumes and complexity of calculations.

Existing standards and methods are regularly found to be too limited or too slow for modern cloud environments. Many models were once designed for stand-alone applications, and proved difficult to transfer to flexible cloud platforms. In addition, architectures often become too heavy or too rigid if they are fully standardized immediately. This hinders innovation and collaboration. What works today for one computation model must also work tomorrow for dozens of models that run simultaneously. Think of functionalities such as:

- Real-time processing of large data flows;
- Automatic scaling of computing power via the cloud;
- Management of model chains where the output of one model is input for the following;
- Use of container technology (such as Docker) to run computation models flexibly, quickly and on different systems.

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[78] https://csfm.ethz.ch/en/research/integrative-projects/digital-twin/odtp.html

Instead of standardizing everything in advance, a practical approach is also needed. This requires a holistic view of performance: not only fast hardware, but also smart software and flexible infrastructure. Start with small pieces of interoperability between models and systems, and then expand those successes. For example, pub/sub-mechanics, notebooks, container technology, Graphics Processing Units (GPUs) and scalable cloud technology play an important role. In the following sections, we will discuss these technologies in more detail. Only with smart, scalable architectures, which move with the growing data flows and flexibly deal with collaboration between computation models, can we continue to benefit from the power of digital simulation. This requires a balance between pragmatics and vision: start small, but build with a view to the future by also standardizing.

GPUs make it possible to perform extremely data-intensive calculations, but the need for High Performance Computing (HPC) means that the rest of the infrastructure must also be able to grow with it. This requires, among other things:

- Lots of (server) memory to work with terabytes of datasets;
- API links that are efficient enough to process and share large amounts of data with other systems;
- Fast and smooth data flows to client visualizations. After all, slow streaming or bottlenecks in communication can undermine the entire experience.

In practice, this chain is often underestimated. A GPU alone is not enough. The performance of such a system depends on the interplay between GPUs, CPUs, memory, data connections, algorithms and the design of the software itself.

4.5.4 Publish/subscribe technology

Why is the publish/subscribe mechanism (also called pub/sub) often used in digital twins? This has to do with the calculation of certain scenarios and effects of interventions, which are possible in a digital twin. The digital twins use data, computation models and visualizations to simulate real-world situations. In a digital twin, for example, you can see what happens when you close a street, enter a new traffic plan (a 30 km zone) or place additional noise barriers. To make this all run smoothly, good communication between the different parts or building blocks of a digital twin is essential. This is where the publish/subscribe mechanism comes into play (European Commission, 2023). This mechanism works as a kind of smart messenger of messages between the building blocks:

- The publisher sends messages about changes or events, such as scenarios or action to be taken, e.g. ‘the road is closed’;
- The subscribers are the building blocks or components of the digital twins, which automatically receive these messages, for example a traffic model that wants to know when roads are closed and the sound model can calculate the sound effects of the road closure;
- There is a message broker between the publisher and subscribers, which ensures that every message reaches the right subscribers, without the sender and recipient having to know each other.

In a digital twin, data is constantly changing. Think of the above-mentioned adjusted traffic flows, new noise or air quality calculations that a policymaker wants to see when he closes a busy street in a digital twin. As soon as he enters this change via an interface:

1. Changes are published and automatically shared with all relevant computation models on the pub/sub-system;
2. The different computation models, such as traffic, environmental and noise models, automatically receive notifications of changes and calculate the impact;
3. The results are automatically visualized in the digital twins.

Applying the publish/subscribe mechanism also keeps the computation models in a digital twin in sync, so that all components work with the same information. In short, pub/sub is a mechanism of a digital twin that ensures that all computation models receive the right information at the right time. Without a pub/sub, each component would have to manually retrieve information or connect to each other. This is more complex, error-prone and slower.

4.5.5 Notebooks and Container Technology

Notebooks are interactive, web-based tools that allow users to combine code, text, visualizations, and output into a single document. Well-known examples are Jupyter Notebooks, Google Colab and Deepnote. These tools are widely used in scientific computing and data science. Researchers can perform the computation models and directly view and adjust the results in interactive workflows. Scientific researchers and modellers use Notebooks to set up, calibrate and execute computation models. These tools include interactive cells for input parameters, simulation output, and visualizations in real-time charts and model output maps. Notebooks are relatively user-friendly, as researchers can execute complex models without in-depth knowledge of command-line tools or programming environments. Notebooks combine code with explanations and results that promote transparency and reproducibility, and support multiple programming languages (such as Python, R, and Julia) that are commonly used in the scientific circles of modellers.

Containerization is a technology that packs software applications and their dependencies into an isolated environment, a container, so that they can run consistently across computer systems. Containers are lightweight, self-sufficient environments, which contain everything an application needs to run, such as the (runtime) code of the application, the libraries and dependencies and any file systems and configurations. Each computation model is packaged in a container, which contains all the necessary software and libraries. This eliminates dependency problems. Containers are light (using less computing resources), start up faster and are platform independent (doing the same regardless of the underlying system on a laptop, server, cloud environment or HPC cluster). Docker is a widely used tool for creating, distributing and managing containers. In combination with Kubernetes, it provides a platform to manage containers at scale in production environments. Containerization is ideal for modern software development and scientific applications such as modeling and simulations.

By combining Notebooks and Containers, each simulation can be fully reproduced. Other researchers can easily use the same Container and Notebook to validate or improve results. In some Dutch scientific projects, computation models in digital twins have been brought together via Notebooks and Containers, such as in the LTER-LIFE infrastructure for ecological modelling and the Destiné Adaptation Modelling Framework in the field of climate adaptation (see box).

Application – LTER-LIFE research infrastructure

LTER-LIFE[79] is a large-scale Dutch research infrastructure in the making. The aim is to provide a state-of-the-art infrastructure to study and predict how changes in climate and other man-made pressures affect ecosystems and biodiversity. The LTER-LIFE approach is one of ‘digital twins of whole ecosystems’. A LTER-LIFE digital twin is "a digital replica of a living or non-living physical entity". Building digital twins of ecosystems has only recently become possible by developing and making available the large amounts of data needed for this domain, artificial intelligence, advanced computing infrastructure and the FAIR principles.

A digital twin of an ecosystem provides tools to integrate data on abiotic factors (e.g. nutrient deposition, temperature, drought), biotic factors (e.g. data on the long-term occurrence of animals and plants) and human activities (e.g. tourism, agriculture, fisheries). It provides diagnostic data-driven and dynamic process-based computation models in one logical place ensuring the necessary

[79] https://lter-life.nl/en

interoperability, scalability, storage and processing capacity. LTER-LIFE brings together data scientists, computer scientists and ecologists in ecosystem research communities. To produce digital twins of entire ecosystems, LTER-LIFE will develop an infrastructure, which includes a virtual research environment and services, catalogs and repositories that contain FAIR data, models and software tools such as Notebooks and Containers.

Application – Destiné Adaptation Modelling Framework

Deltares, among others, is working on the Adaptation Modelling Framework (AMF) in Europe.[80] AMF is an initiative within the Destination Earth program, aimed at supporting the EU climate adaptation strategy. The aim is to provide decision-makers with easier access to advanced models for analyzing the dangers and impacts of climate change. Although advanced open-source models exist for flood risk, for example, they are often complex and require specific technical expertise.

A digital twin for flood risk management has been developed within the AMF, which automates processes and enables non-technical users to evaluate different scenarios. AMF has the following basic characteristics:

1. It uses a modular design approach, which promotes collaboration, innovation and knowledge exchange. This ensures that digital twins are constantly evolving to respond to emerging needs and integrate the latest scientific developments;
2. By automating model preparation and workflows, the AMF makes complex models accessible to a wider range of users, which is essential for effective decision-making in digital twins;
3. The use of containerization (such as Docker) within the AMF facilitates the scalability and reproducibility of models, which is crucial for reliable and consistent results in digital twins.

By integrating these approaches, digital twins can be used more effectively for adaptation planning and flood risk management with improved accessibility and reliability of computation models.

4.5.6 Graphics Processing Units

Calculations in digital twins based on Graphics Processing Units (GPU) are essential due to the need to process large amounts of data quickly and efficiently (Lohman et al., 2023). GPUs are designed for parallel processing and high computing capacity. They contain thousands of small cores, which can perform computational operations at the same time, which is much faster than traditional CPUs in tasks such as matrix operations and simulations. GPUs split large datasets into smaller parts and perform the same calculation on each part at the same time. The data is transferred from the CPU memory to the GPU memory, where the calculations take place. Specific programming languages, such as CUDA (for NVIDIA GPUs) and OpenCL make this possible and are used to write GPU processing algorithms. This is particularly suitable for simulations with many repetitive calculations, such as traffic models, flow models or ray tracing for realistic visualization. Modern digital twins optimize this transfer to minimize delay.

For example, the use of GPUs makes sense when calculating real-time or near-real-time simulations and dynamic scenarios for, for example, water flow dynamics (hydrological modelling), traffic models and crowd simulations. In the Netherlands, some digital twin systems have been developed, relying on GPUs, such as Tygron Platform, Urban Strategy and SIMCrowds (see boxes).

Application - Tygron Platform

Tygron implements GPU-based HPC & AI computation models81 for performing complex urban and environmental simulations, such as flooding, heat stress, object recognition, noise and traffic flows.

[80] https://destination-earth.eu/use-cases/adaptation-modelling-framework/
[81] https://www.tygron.com/en/gpu/

Thanks to the GPU, Tygron is able to perform real-time simulations on comprehensive GIS datasets, including 3D city models and, for example, calculate the impact of precipitation on urban areas, both before and after implementing a climate-adaptive measure. This is also possible in high resolution and it is therefore possible to build the computation model directly from OGC GIS data that are supplied via various API links. Tygron manages a compute cloud environment where users can log in (or link with) and perform different simulations in parallel. The results are presented in real time, allowing users to plan and analyze interactively with the platform. It then visualizes the results via various client (web) applications, including an interactive 3D environment.

Application – Urban Strategy

Urban Strategy82 by Scenexus, a spin-off of TNO, also uses GPU technology to accelerate complex simulations of mobility in urban areas, such as traffic flows, air quality, and noise pollution. The use of GPUs allows Urban Strategy to perform integrated analyses using interlinked computation models of multiple urban systems within a single platform. (Lohman et al., 2023) The platform distributes computationally intensive tasks (such as air displacement and traffic movements) over GPU cores, which dramatically increases the computational speed. Urban Strategy helps with decision-making by simulating urban planning and mobility scenarios, for example the impact of traffic measures on emissions and noise pollution or the introduction of 30km zones or zero emission zones in large cities. Urban Strategy's ability to process large datasets without delay allows users to get immediate feedback on their scenarios and simulations.

Application – SIMCrowds

SIMCrowds83 was developed by UCrowds as a spin-off of the University of Utrecht and also makes intensive use of GPU-based calculations. These are crucial for crowd simulations, as they provide the high computational capacity needed to simulate in real time the behavior of large numbers of individual agents (actors with their own behavior such as people in vehicles, etc.). Crowd simulations involve thousands to millions of agents, with each agent dynamically responding to the environment and other agents. This requires a huge amount of computing power for parallel calculations such as route planning and collision detection. Each agent in a simulation performs largely independent calculations, such as determining an optimal route, adjusting speed in emergency situations or changes in infrastructure. The GPU processes continuous updates to the simulation environment, such as changing obstacles or adjustments to agents' goals. By deploying GPUs for collision detection, SIMCrowd calculates in fractions of seconds whether agents need to stop, accelerate, or adjust their route to avoid collisions.

Specific algorithms, such as boid algorithms for swarm behavior or crowd dynamics models (e.g. Helbing's Social Force Model), are optimized for GPUs using programming languages such as CUDA or OpenCL. GPUs support not only the calculations, but also the rendering (e.g. WebAssemby) of the simulation in a 3D environment, allowing users to instantly see how a crowd moves and reacts. This makes crowd simulations ideal for GPUs, which contain many computational cores to perform such calculations in parallel. In applications such as evacuation planning or event management, real-time simulation is essential because time-critical decisions are made. GPUs can deliver this speed.

4.5.7 Cybersecurity

As digital twins become more complex and accessible and are linked to more and more computation models, data (sources) and cloud services, the risk of digital attacks is also increasing

[82] https://www.scenexus.com/urban-strategy/

[83] https://ucrowds.com/simcrowds/

sharply. Cybersecurity is therefore no longer an afterthought, but a hard precondition for the responsible use of digital twins. You can still have such a powerful computation model, with streamlined API links and high-quality data, if the system is unsafe, you will lose everything:

- If data is stolen or deleted in an attack, you lose the foundation of your simulations;
- If the uptime is unstable due to DDoS attacks or server intrusions, you as a user can no longer count on a reliable system;
- If third parties gain undetected access to your system, privacy, policy sensitivity and integrity are also at risk.

This is not a hypothetical risk. Experience shows that online computing platforms, such as the Tygron Platform, are attacked hundreds of times a day. And that is by no means an exception. It is everywhere, as is also confirmed in the threat picture of the national government[84].

Cybersecurity is not only a technical challenge, but also a policy challenge. The Dutch Cybersecurity Strategy 2022-2028 makes this clear and states that digital products and services must be secure and innovative. Digital twins, which often serve as a central link in policy information and decision-making, are directly covered. Therefore, it is important that digital twins:

- Operate on safe and reliable infrastructure (preferably within the Netherlands);
- Continuous monitoring against attacks;
- ISO 27001-certified and – where necessary – tested by external ethical hackers at major releases';
- Apply clear policies for access control, encryption and data security.

When it comes to quality assurance of digital twins, cybersecurity should be a fixed pillar, and just as important as model validation or data quality. Design choices should be based not only on performance or scalability, but also on protection against threats. Especially now that digital twins are more often accessible via the internet and are linked with multiple parties, it is essential that safety is included in the design from the start. A digital twin without robust security is vulnerable to disruption, sabotage and abuse.

4.6 Usage aspects of computation models

During the discussions, some aspects that are important for the responsible use of models were also discussed. This included the application of the FAIR principles for accessibility and usability and quality assurance in the development and use of computation models. We discuss these aspects below and then conclude with a critical reflection on the relationship between computation models and digital twins and initiatives that can contribute to good practice.

4.6.1 Accessible and usable computation models

The FAIR principles from the open science movement are a set of guidelines to make data accessible and usable. (Wilkinson et al., 2016) FAIR stands for Findable, Accessible, Interoperable and Reusable and applying these principles to computation models ensures that computation models are more shareable, reusable and understandable. Janssen *et al.* (2023) have formulated a number of principles that indicate what computation models must comply with in order to be considered FAIR:

- Computation models must be uniquely identifiable and findable via descriptions and metadata through search engines and/or an algorithmic or computation model register;
- Access to computation models should be simple and clearly regulated, where possible computation models should be made available as open tools, for example through licenses

[84] https://www.rijksoverheid.nl/documenten/publicaties/2022/10/10/nederlandse-cybersecuritystrategie-2022---2028

such as Creative Commons, within the limitations of rights and privacy. For sensitive models (e.g. ownership models), access rights are regulated through authentication and authorization;

- Computation models and their metadata should be easily combinable with other datasets and tools. Models should use standard data formats that are widely supported. Metadata and terms are harmonized through semantic standards, such as ontologies. Computation models also have user-friendly access via standardized interfaces, such as RESTful APIs. Creating computation models in FAIR not only involves semantic interoperability, but also technical aspects of interoperability;
- After all, computation models are well documented so that they can be reused in different contexts. They are described with clear manuals, instructions for use and restrictions. The history of model updates is recorded to ensure consistency. For quality assurance, audit and verification reports are prepared to increase confidence in the model.

In the scientific world, the FAIRification of computation models receives a lot of attention. Making models FAIR[85] is an international initiative to improve skills, practices and protocols to create FAIR computation models (Barton et al. 2022b).

4.6.2 Ensuring quality of computation models

Another aspect that is frequently discussed in the conversations is the responsible use of computation models in digital twins. Basically, this is about the question: which computation model should I use and does the computation model meet certain quality requirements?

There are risks associated with the use of computation models whose quality is not sufficiently guaranteed. In the recent past, political considerations (e.g. the nitrogen dossier) have been seriously complicated after discussions have arisen about the quality of the model tools used in policy advice. There is also a risk of a loss of efficiency in the policy process when shortcomings in the model calculations by digital twins need to be corrected because, for example, (input) data proves to be incorrect, processes are not accurately mimicked or the computation models were not fully suitable for the application. Quality assurance aims to mitigate these risks and is therefore relevant for all users and stakeholders.

Wageningen University & Research has been working on a quality assurance framework for its computation models in recent years (see Figure 17). As part of this, a protocol has been drawn up with 22 requirements that each new computer model must meet. The protocol is available online as a handy checklist[86] (Hengeveld, 2020) and helps Wageningen modellers in the development of their model, in assessing the applicability of the model and in getting a grip on necessary investments in model maintenance. By testing a computation model against this protocol, modellers show that this is a reliable model.

The protocol uses a self-assessment method, which modellers can use to indicate when the computation model can and cannot be used. The use of the protocol also provides insight into where more investments in the computation model should take place (to get them better and keep them good). The protocol also points a modeller to imperfections or ambiguities in its descriptions and analyses and improves communication about computation models with policy makers and directors (management and clients). The auditors of the computation models read all documentation and descriptions of models and tests that meet the requirements that a WUR model should meet. A detailed description of the computation model is essential. What is the purpose of the model and what can it be used for and what can it not be used for? The results of the model should also be analyzed: what is the sensitivity to variation in the input data, what uncertainties do the model and the underlying data have? This method also contributes to planned work: Know and

[85] https://www.tobefair.org/
[86] https://magazines.wur.nl/kb-magazine-2023/a-checklist-for-quality

record who does what and who has what responsibility. However, quality assurance comes at a cost. Ultimately, it is the balancing of these costs against the risks mentioned above that determines whether an investment in quality assurance makes sense.

Models, Datasets and Indicators
Models, datasets and indicators allow for standardised interpretation and efficient re-use of scientific insight and efforts. Policy and decision support based on models, datasets and indicators is embedded in software and webservices or incorporated in reports and policy briefs. Documentation on scientific considerations, operational efficiency and user interpretation remain hidden.

Perspectives on quality
We present a checklist for the quality of models, datasets and indicators from three perspectives: scientific (topics 1 - 4), development (topics 5 & 6) and end use (topic 7).
These perspectives relate to scientific rigor, efficiency of operation and the interpretation of results.

Requirements and criteria
Within the 7 topics 22 requirements are defined. For each requirement an elaborate formulation of criteria to be met is available. By providing references to the documentation related to these criteria, the checklist provides a reading guide to the model, dataset or indicator.

WAGENINGEN
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A checklist for the
Quality of Models, Datasets and Indicators
to be used in policy and decision support

2020

Checklist

1. The model/dataset/indicator description ☐
- a. There is a general description ☐
- b. The conceptual and formal model are described ☐

2. The technical implementation ☐
- a. The implementation is documented ☐
- b. The technical environment is described ☐
- c. The implementation is tested ☐

3. Parameters, variables, inputs and output ☐
- a. The parameters and variables are documented ☐
- b. Calibration of parameters is described ☐
- c. Input and output is described ☐
- d. The provenance of input data is described ☐

4. Evaluation ☐
- a. A sensitivity analysis is performed ☐
- b. An uncertainty analysis is performed ☐
- c. The model / dataset / indicator is validated ☐
- d. The use is monitored ☐
- e. There is a general assessment of quality ☐

5. Planned development ☐
- a. There is a development plan ☐
- b. A version control system is in place ☐

6. The organisation ☐
- a. The metadata is available ☐
- b. There is a management plan ☐
- c. Dependencies are discussed ☐
- d. External use is formalised ☐

7. User documentation ☐
- a. Interpretation guidance is provided ☐
- b. There is a user manual ☐

QUALITY SYSTEM

INDICATORS
MODELS
DATASETS

A

Further information
Detailed description of the requirements and information on the use of this checklist in the quality assessment of models, datasets and indicators at Wageningen Research can be found in the accompanying leaflet or by contacting Geerten.Hengeveld@wur.nl

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Figure 17 - Checklist for the quality of computation models (Hengeveld, 2020).

4.6.3 Good modeling in practice

The responsible application of models is not easy and a helpful tool for this is the "Good Modelling Practice" manual. This was originally developed to provide guidance for the responsible development, use and evaluation of computation models in policy and decision-making processes (Waveren et al., 1999). The handbook has been drawn up by various Dutch government bodies and scientific organizations, such as Rijkswaterstaat and TNO, and focuses mainly on the use of models in the physical environment, such as water management, the environment, and infrastructure. It serves as a practical framework for both model developers and users in policy processes, with a strong focus on transparency, uniformity and explicitly dealing with uncertainties.

The handbook follows the life-cycle approach of a model: from specification of goals and requirements, development and implementation to validation, calibration, and sensitivity analysis. As a final step, attention is paid to the application of the computation model in policy and decision-making and communication. Attention is paid to how uncertainties in data and model assumptions should be made explicit and communicated. And the handbook emphasizes the importance of collaboration between model developers, policy makers, and other stakeholders (team process). Guidelines for documenting computation models ensure that the assumptions, methods and outcomes can be understood and reproducible. The manual thus helps users to use computation models effectively and responsibly.

The Manual was originally designed to ensure the reliability and reproducibility of models. During the meeting ‘Good Modelling in Practice’ on 13 June 2024, organized by the Nederlandse Hydrologische Vereniging (Netherlands Hydrological Association) and STOWA, 25 years of Good Modelling Practice was celebrated. The fifty participants reflected on the topicality and applicability of the manual in water management and management. The overall conclusion was that it remains relevant as model results increasingly play a crucial role in political-administrative decision-making. Models are becoming increasingly complex and socially relevant, making the handbook more up-to-date than ever. The included guidelines are often applied indirectly, with modern tools and methods for validation and sensitivity analyses. The growing mistrust of the outside world and the general public calls for more transparency and clear communication about what models can and cannot do. The workshop[87] also resulted in various recommendations and actions for revising the Handbook:

- Take into account new techniques such as scripting for reproducibility and automatic calibration;
- The creation of an independent authority for quality management of computation models, such as a hydrological authority or an independent review network, similar to the Water Safety Expertise Network, was suggested;
- Set up training and certification by developing a ‘Good Modelling Practice’ course and possibly also certification to integrate guidelines into the practice of new and existing modellers;
- Strengthening international cooperation and learning from other countries, such as Belgium, where such exams are taken;
- Public access to a "Good Modelling Practice" Wiki, a digital platform for sharing and updating the handbook, proposed by Wageningen University, was welcomed.

At the end of 2024, STOWA and Rijkswaterstaat launched a call to further develop the ‘Good Modelling Practise’ community.

[87] https://www.stowa.nl/agenda/meeting-good-modelling-the-practice

4.6.4 Setting up an IT infrastructure

The data, computation models and visualizations that are combined in digital twins often come from different suppliers and are available in a variety of locations and platforms. A solid IT infrastructure is needed to combine these elements in a fast and reliable manner. When setting this up, suppliers and users of computation models have to make various considerations. Here we briefly discuss some aspects that are important to enable computation models to function within digital twins: In other words, on which IT infrastructure do the computation models and their building blocks run?

Section 2.2 introduces a modular architecture derived from the reference architecture for European local digital twins (European Commission, 2023). The data, computation models and visualizations run somewhere 'in the cloud' hosted by a supplier or locally ('on-premises') close to the user. The question of where the digital twins 'live' is certainly important for how the digital twins are designed, used and scaled up. The physical location(s) and IT infrastructure where the data, computation models and visualizations run also determine which choices can and must be made about functional and technical management, the entire infrastructure, performance, accessibility, control, ownership, funding and revenue model and cybersecurity. And with that also how computation models are integrated or made available in the twins. This touches on some fundamental questions:

- Where is data stored and processed?
- Where and by whom are computation models performed?
- How close are computation models and data to each other, logically and physically?

There are several options to organize access to computation models in a modular architecture: central to the supplier or platform provider, for example as a web service via an API, decentralized to the user or recipient of the digital twins, or in a hybrid form in which parts of the digital twins run centrally and others locally. The choice for this depends, among other things, on the extent to which the provider allows customers to run or adjust the digital twin and/or computation model independently (locally). For example: can the model only be used via an API, or can it be executed (compiled or not) on the user's IT infrastructure? And are there any technical or legal restrictions built in by the supplier, for example because of assumptions about computing power, storage location or security? In practice, we see different solutions. For example, the green benefit planner at RIVM calculates on the basis of input provided by a user, while Deltares delivers many water models to, for example, water boards as a binary file for which the users themselves control input, output and runtime on their own infrastructure. Computation models can also be integrated into digital twins with data and visualizations. Computation models can also be 'directed' and brought to the data ('data visiting') due to data protection considerations (e.g. 'privacy enhancing technologies').

How access to computation models is organized depends on various considerations that must be made by both the supplier and the customer of the computation model. Typically, a provider of a computation model determines how the computation model is made available. But perhaps the buyer prefers it differently. If the customer can calculate cheaper and more efficiently elsewhere or if calculation and data have to be close to each other, if intermediate data files are very large or too sensitive to share and therefore prefer not to be moved, etc., it may be desirable that the computation model is (un)compiled by the customer elsewhere. This also depends on the level at which the supplier allows customers to make their own applications or adjustments to the model. Substantive, business, strategic or technical considerations can play a role in this. A recent, geopolitical consideration may be to keep storage of sensitive data and simulations within the EU or even its own country. From the perspective of the user, various situations are conceivable in which it is desirable to carry out the computation model elsewhere:

- When the customer can charge cheaper or more efficiently (e.g. via their own cloud resources);
- When data and calculation must remain physically close to each other (e.g. for latency sensitive applications);
- When intermediate files are large or privacy-sensitive and therefore prefer not to be transferred;
- When adjustments to the computation model are needed that can only be done locally or with source code.

4.6.5 A critical perspective

A critical perspective at the use of computation models in digital twins was not lacking in the conversations we conducted. For example, it has been indicated that many models are very complex, so that their operation is not well understood by users. Complex models are also difficult to explain to citizens and therefore sometimes a limiting factor in transparent decision-making. In democratic decision-making, all those involved ideally have the same knowledge and information available. However, information from various complex models plays an important role in many decision-making processes, the origin and reliability of which are difficult for data subjects to estimate. This leads to two opposite reactions. On the one hand, there is a tendency to rely too much on models as an objective representation of processes in reality. Especially if results of computation models are presented very convincingly, this leads to a risk of overestimating their accuracy. On the other hand, the high black box content of models can contribute to distrust of the results and a tendency to ignore them. This highlights the importance of clear communication about the functioning and limitations of models.

In the interviews, some also indicated that unrealistic expectations are regularly created about the application possibilities of computation models. For example, the ambition to answer all policy questions with a single model or an integrated digital twin is considered problematic. Linking different computation models with different assumptions and scales can produce inaccurate or misleading results. An important, related question is: which computation model fits best with (this part of) the planning task or research question that arises. This fit-for-purpose not only concerns the reliability of the model, but also aspects such as connection to the case (saliency) and the stakeholders (legitimacy). For an in-depth discussion, see: Hamilton et al. (2022).

In addition, the lack of explicit communication about the uncertainties is mentioned as a concern. Computation models often present results without providing clarity about the uncertainties and assumptions that underlie them. This can lead to misinterpretations by policymakers and other users. Limited validation and reproducibility is also considered a risk. Validation of computation models is often not done systematically enough, and reproducibility is a challenge, especially for non-experts. This reduces legitimacy and confidence in models.

Finally, confirmation bias is mentioned as an argument against the ill-considered use of computation models. As soon as a model is considered proven, hardly anyone dares to critically assess it anymore. This can lead to an unhealthy status quo in the use of computation models.

On the basis of these counter-arguments, various recommendations have also been made to avoid problems of interpretation, shortcomings and risks. To name a few:

1. Develop less complex models, which are more transparent and easier to understand and reproduce, also for citizens;
2. Provide explicit communication about uncertainties and value-driven choices in computation models to users, including policy makers;
3. Validate computation models regularly with (new) observations and make sensitivity analyses a standard part of the modelling process;

4. Limit overlinking of computation models and do not aim for integrated models that try to cover everything, rather develop more specific models per demand;
5. Increase democratization and participation, with citizens and stakeholders having a say in what computation models should represent and how they are used. This is also known as participatory modelling;
6. Focus on fit-for-purpose, so that computation models are designed and certified for specific purposes, rather than trying to be universally applicable; and
7. Promote openness, transparency and collaboration by sharing model codes and documentation.

5. Findings and recommendations

Digital twins are digital representations of reality that enable the analysis and simulation of complex issues in the physical environment for current issues such as climate adaptation, energy transition, infrastructure, housing and urban development. Digital twins aim to support policy, planning and decision-making by linking real-time insights, analyses, simulations and predictions to issues to be solved.

Basically, digital twins consist of data, computation models and visualizations. To achieve more efficiency, shared insights, time savings and lower costs, the Netherlands is now working on a national network of local digital twins. This network should make it possible to use each other's data, computation models and visualizations. Data sharing has gained a lot of experience in recent years. However, connecting calculation models is still largely unexplored territory, while this is precisely where gains can be made in solving major social challenges. This exploration therefore focuses on the interoperability (the ability to collaborate and exchange information) of computation models within digital twins.

Computation models are used in digital twins to analyze, simulate, or predict aspects and processes of the physical environment with the ultimate goal of supporting decisions and making interventions. Computation models vary widely in function, model approach, and application domain, and can be descriptive, predictive, simulating, or optimizing. Models are designed with a specific question or problem in mind, so they often have specific applications in defined areas such as water management, energy transition, climate adaptation or mobility. For every application, the use of computation models requires attention to validation, uncertainty analysis and iteration to deliver accurate, applicable results.

In many complex societal questions, various, diverse aspects (human, environmental, economic, etc.) play a role, while an integral consideration is often desired. Digital twins can contribute to integral solutions to such questions by combining (outcomes of) various models. However, given the different objectives, design and nature of the computation models, this is not an easy matter. We discussed the (im)possibility of combining and exchanging computation models within digital twins with various experts from the Dutch field. They are professionally involved in computation models in digital twins and have highlighted various legal, organizational, semantic, technical and user aspects of interoperability.

In order to stimulate the interoperability of computation models in digital twins, a number of recommendations were formulated on the basis of the discussions held with the experts and from their own desk research. These have been done in view of the various implementation programs in the Netherlands, including DMI DTaaS, so that this leads to actions to further implement interoperability of computation models in the Dutch practice of digital twins. We summarize the main findings, the resulting recommendations and follow-up actions below. These are grouped into a number of recurring themes: strategy, collaboration, business models, quality assurance, standardization and high-performance computing/AI.

Strategy

Several governments and companies use digital twins for simulations, but without clear policies and infrastructure, applications are limited to individual projects. A national roadmap can help determine how digital twins can be deployed consistently and scalable. This can be achieved through the following actions:

1. Develop a roadmap for digital twins in the Netherlands. This provides a long-term strategy for interoperability and cooperation.
2. Sharing computation models is not easy. Often this is not primarily due to technology, but rather to semantics and governance. Further study of these aspects is desirable.

Cooperation and knowledge sharing

Cooperation between institutes, companies and governments is crucial to make agreements and to develop and adopt standards. The collaboration between different disciplines and domains reduces duplication of work and accelerates innovation. Knowledge sharing spreads best practices, leading to wider adoption of new technologies. There is a strong need for regular meetings and testbeds to test new techniques and share experiences. Regular workshops and conferences can promote awareness and adoption. Open communication on modelling, quality aspects and application domain can contribute to wider acceptance of model-based outcomes among policy makers, citizens and other stakeholders. Complexity is at odds with transparency and insight into correct applications. The ideal model is as complex as necessary and as simple as possible.

The following recommendations have been made:

1. Promote openness, transparency and collaboration by sharing model codes and documentation. Provide explicit communication about uncertainties and value-driven choices in computation models to users, including policy makers;
2. Increase democratization and participation, with citizens and stakeholders having a say in what computation models should represent and how they are used (participatory modelling);
3. Develop less complex models, which are more transparent and easier to understand and reproduce, including for citizens;
4. Focus on demonstration projects, which have the potential to be scalable in cooperation with municipalities and companies, for example for water management and mobility;
5. Facilitate knowledge sharing through workshops and conferences. Start an annual conference on digital twins and model management. This encourages collaboration and provides a platform to share results;
6. Organize trainings and workshops to share the knowledge about (the pros and cons) of using computation models in digital twins in daily practice. Develop knowledge programs focused on the use and interpretation of models. Users should be trained to use the new tools and standards effectively;
7. Explore funding opportunities and cooperation through European programs such as Horizon Europe, Digital Europe or national grants.

Earning models

There are already several ways to fund the further development of digital twins and computation models, such as subscription services and/or through licenses. As computation models become more modular and interoperable within digital twins, new questions arise about determining the value, pricing and licensing conditions for these services. User groups have different priorities, such as essential datasets, accurate predictions and access to specific computational functionalities, affecting the provision and valuation of computation modelling services.

This leads to the following recommendation:

1. In addition to the technical challenges, it is essential to explore earning and pricing models in order to determine the value of using computation modelling services for different target groups, including public and private parties;
2. Create licensing terms that offer flexibility to users while protecting the intellectual property rights of providers, paying attention to the needs of different user groups.

Quality assurance

Computation models are not always used for what they are intended and are not always validated before they are used. Quality frameworks and audits are necessary to ensure reliability. There is a need for quality frameworks to determine when a model is suitable for a particular use. This requires a clear view of fit-for-purpose and quality and reliability in relation to the intended application (validation and certification). Unreliable models can lead to wrong decisions in critical areas, such as infrastructure and nature management. The lack of quality control also inhibits scientific progress and the use of scientific results (computation models) in policy. Computation models are also not always findable, accessible, interoperable and reusable, so FAIR. This requires clear guidelines, such as adding metadata and following guidelines.

The Handbook of Good Modelling Practice can contribute to the reliability and acceptance of computation models in digital twins. By applying the Handbook, model results can not only be better understood, but also more widely accepted by policy makers and the public:

- Making objectives, model assumptions and the scope of operation of computation models explicit ensures transparency;
- The use of standardized processes and tools that promote consistency ensures reproducibility; and
- Validation and legitimation provide a reliable basis for decision-making and integration of computation models into digital twins.

The following recommendations have been made:

1. Introduce a quality framework for computation models such as those developed by the WUR and collaborate with knowledge institutions such as WUR, PBL and Deltares. Adopt a quality framework that can count on broad support and that links quality to application domain. Focus on fit-for-purpose, so that computation models are designed and certified for specific purposes, rather than trying to be universally applicable;
2. Validate computation models regularly with (new) observations and make sensitivity analyses a standard part of the modelling process;
3. Explore the possibility of a national model register to make computation models discoverable, including metadata and certifications. A national design register shall promote transparency about available computation models and their quality and promote re-use. Find cooperation with the algorithm register;
4. Conduct audits to ensure model quality. This increases confidence in the results of computation models and stimulates their use in practice.

Standardization

The importance of standardization stems from the need to link and jointly use computation models, which are developed in different domains, in digital twins for the various applications in the physical environment. The integration of dynamic computation models is particularly challenging. Without standardization, computation models remain fragmented and difficult to re-use. Time and resources are also lost on tailor-made solutions for model couplings, which hinders innovation. Standards such as OGC API Processes and Basic Model Interface are important to link computation models and improve interoperability. Standardization is important to make models work better together, but it does not mean striving for universal models that can be used for a wide range of applications.

To enable collaboration between computation models, workflow management is needed in combination with new technologies, such as containerization and GPU-based processing platforms (cloud and on premise). The Open Digital Twin Platform (ODTP) provides a comprehensive infrastructure for workflow management within digital twins. By combining standardized interfaces, automation tools and quality assurance, ODTP improves the collaboration between computation models.

The differences in technological platforms often complicate the linking and integration of computation models. Working with different technical platforms and infrastructures often creates obstacles to model integration, such as differences in applied programming languages and performance requirements. New technological tools such as Notebooks and Containerization (such as the often mentioned Docker) help with the modular architecture approach for integrating computation models within digital twins. The use of tools such as Docker and cloud-based solutions is recommended. Notebooks make workflows more transparent and accessible, while Docker ensures reproducibility and scalability. Together, they provide a modern and efficient platform for researchers and policy makers to better address challenges with computation models.

The following recommendations have been made:

1. Limit overlinking of computation models and do not aim for integrated models that try to cover everything, rather develop more specific models per demand;
2. Organize meetings to share knowledge about the Basic Modelling Interface and OGC API Processes and integrate these standards into future digital twins. Perform further testbeds to test the technical standards such as OGC API Processes and Basic Modelling Interface for their applicability to different types of models. Apply these standards in national and European projects;
3. Explore the possibilities of workflow management, such as OGC API Processes and ODTP in combination with technologies, such as publish/subscribe technology, containerization and GPU-based processing platforms to enable collaboration between computation models;
4. Develop a national guidance for interoperability. This gives developers and policy makers concrete guidelines. Focus on the use of models in digital twins.

High-Performance Computing and AI

High-performance computing is also beginning to find its application in digital twins. The use of multi-threaded computing and GPUs is recommended to enable large-scale simulations. GPU-based calculations are essential for accelerating complex simulations in digital twins. These platforms use GPU technology to make data-intensive computing models more efficient and scalable. They enable real-time analytics, improve user experience, and support detailed urban planning and policy making. AI algorithms are also increasingly being used for simulations and model validation in digital twins. The integration of AI algorithms with existing computation models and digital twins can increase the efficiency of existing systems and enable new applications.

The following recommendations have been made:

1. Pay attention to high-performance computing and the role of workflow management and container technology in this and research which standards can play a role in this;
2. Explore the role of AI for model optimization and research applications of AI for validation, simulation and prediction in digital twins;
3. Explore the collaboration for high-performance computing for model integration and model innovations in digital twins with companies and research institutes such as the TO2 federation.

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Annex 1 - Experts consulted

(in alphabetical order last name)

Fedor Baart	Deltares
Björn Backeberg	Deltares
Niels Drost	Netherlands eScience Center
Tessa Eikelboom	Rijkswaterstaat
Yann Friocourt	Rijkswaterstaat
Roland Gerearts	University Utrecht / UCrowds
Joep Grispen	Nelen & Schuurmans
Jene van der Heide	Wageningen University & Research
Geerten Hengeveld	Netherlands Institute for Ecology (NIOO-KNAW)
Maarten Hilferink	ObjectVision
Bert Jagers	Deltares
Peter Kalverla	Netherlands eScience Center
Maxim Kepflé	Tygron
Maurice de Kleijn	Netherlands eScience Center
Walter Lohman	TNO
Lieke Melsen	Wageningen University & Research
Ton de Nijs	National Institute for Public Health and the Environment (RIVM)
Erik Oudejans	ObjectVision
Nico Pieterse	Netherlands Environmental Assessment Agency (PBL)
Johan van der Schuit	Netherlands Environmental Assessment Agency (PBL)

Annex 2 - Questionnaire

The following questions have guided the interviews with experts on interoperability and the use of computation models in digital twins. The questionnaire is designed to address the key points of technical and organizational interoperability.

Context and experiences

1. From what context and experiences are you conducting this conversation?
    - Sector, theme, or specific model(product)?
2. What type of calculation models do you use, and what are the most important applications?
3. Who are the primary users of the calculation models, and what are their needs?

Bringing data and calculation models together

4. What methods do you use to bring data and models together?
    - Orchestration: A central component links data and models via an interface.
    - Data-driven: The model starts as soon as it receives data and produces output.
    - Data-visiting: In the case of large datasets, the model is brought to the data.
5. Do you use specific standards (e.g. for orchestration or data-driven processes)?

Approach and disclosure of calculation models

6. How do you approach calculation models?
    - Through a proprietary interface, a domain-specific standard, or a generic standard (e.g., OpenMI, BMI, SISO, OGC API Processes)?
7. Which (inter)national initiatives for model interfaces are you familiar with, and do you have implementation experience?
8. How do you unlock calculation models?
    - Via interfaces (e.g. REST API), as software (e.g. Docker containers), or as compilable code?

Support and certification

9. What support options are necessary?
    - Standards for data provenance (e.g., lab logs for reproducibility).
    - Certification of models or implementations by software vendors.
10. Is there a need for agreements on model deployment?
    - For example, use of standard containers, documentation or support from experts.

Further interoperability

11. Are specific additions needed to existing interface standards?
12. Are additional agreements needed for public-private partnerships (e.g. to support standards set by the public sector)?

Revenue models and collaboration

13. What are the main challenges and opportunities in developing revenue models for computation models in digital twins?
14. How can cooperation between public and private parties be stimulated to achieve interoperable solutions?

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