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The Technology Monitor 2022

Digital Twins in an Urban Environment

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Commissioned by
The Netherlands Study Centre for Technology Trends
(Stichting Toekomstbeeld der Techniek)

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der Techniek

Colophon

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NUR-nr. 950

Keywords:
Technology, Digital Twins, Future, Innovation, Netherlands

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Foreword

Digital twins are everywhere. These particular types of twins are not just used by high-tech start-ups but also by mainstream companies and government institutions. Digital twins are built to mirror production processes in companies, to mirror complex systems like energy production and distribution utilities, to mirror key assets like bridges and sluices, as well as the entire water management system in the Netherlands. The fact that digital twins are everywhere may conceal that the term digital twins refers to different things. This report will clarify that. How and when did the concept of digital twins come about? Is the concept already applied on a large scale in society or is this a hype that still needs to be implemented to the full? If it has not yet been applied on a large scale, what are the main barriers to large-scale implementation? This report will track the historical path of the emergence of the concept and investigate possible barriers to its large-scale implementation. Finally, we will sketch possible future developments for this fascinating concept.

Roland Ortt
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May 2023

This report is part of a series of reports in which technologies are explored. The reports focus on different technologies. Autonomous vehicles, augmented reality, 3D-printing and blockchain (Ortt & Dees, 2018), quantum technologies (Ortt, 2020) hydrogen green energy and smart roofs (Ortt & Schmidt, 2021) have previously been investigated.

I would like to thank STT for helping to turn my research into an instrument, the Technology Monitor, and for staging that instrument at events and in publications that are available for a wider audience. I have learned that in applied science one of the best ways to develop scientific concepts, models and frameworks is to apply them in practice with a constructive and engaged commissioner. The directors of STT, first Patrick van der Duin and now Rudy van Belkom, have always played an important role as commissioner and sparring partner. It is of great benefit to work this way.

In the current report, several members of STT and various stakeholders in the STT network, are involved with technological innovation in urban environments. These members are either part of a municipal organisation, the organisation of the combined Dutch municipalities *(Vereniging Nederlandse Gemeenten)* or are active in advising municipalities. We requested several of these members to join the *'Klankbordgroep.'* We would like to thank the members of the klankbordgroep. For the second part of the report, we interviewed several people. We would like to thank all of our interviewees who so openly shared their ideas and experiences: Jan Duffhues, Wietse Balster, Bruno Ávila Eça de Matos (Amsterdam municipality), Margriet Heessels (Breda municipality) and Rob Nijkens (Den Bosch municipality), Stefan Los (Den Haag municipality), Noor Bouwens and Arny Plomp (Province Noord Holland), Martin Pot (on digitalisation in the built environment) and Saskia Vlaar (on digitalisation in a corporate context). A workshop was organised for STT members in collaboration with Capgemini. We would like to thank all the workshop participants for their invaluable contribution.

The fact that digital twins are everywhere may conceal that the term digital twins refers to different things. This report will clarify that.

Executive Summary

For whom is this report?
This is a report about digital twins. The report is particularly interesting for professionals developing and applying digital twins in public spaces. Most of these professionals will work for governmental institutions, for example municipalities, provinces or the Dutch government. This report is also about an approach, referred to as the Technology Monitor, exploring the history, the current status and potential future paths of development and diffusion of a well-defined technology. The report is therefore also interesting for researchers involved in technology management and futures studies.

The report is divided into three parts

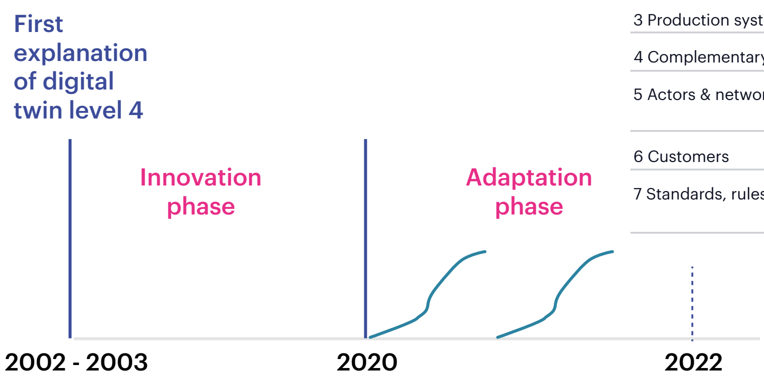
Part I

The first part describes digital twins, using the Technology Monitor. As part of this approach we define ‘digital twins’. Many different definitions of digital twins can be found. We noticed that these definitions can be categorized into four types. We conclude that the term digital twin is used for fundamentally different systems. Higher level digital twins encompass all the aspects of lower level digital twins. That means that higher level twins are, at least technologically, more advanced.

The first level is digital representation of a (base) system, this means that the design of a component, a building or the sewage system in a municipality can be represented and looked at from different angles and distances. Sometimes different layers of information can be added to this representation. But the presentation is static. The second level adds simulation as an extra functionality to level 1. This means that processes or activities are simulated, for example how water flows through a sewage system. The presentation becomes dynamic. The third level uses real-time data from the base-system and connects the base system with its digital representation. This means that the digital twin can be used to monitor the base system’s operation, for example by providing a real-time update about the current capacity of the sewage system after heavy rainfall. The fourth level has a direct feedback loop from the digital representation to the base system. This means that the digital twin automatically and directly manages or controls the base system. For example, a fourth-level digital twin can automatically divert the flow in the sewage system to prevent system overload and flooding. Higher levels may be more advanced technologically, but it may be highly desirable to deliberately require human checks and approval before the digital twin's suggestion are implemented automatically as interventions in the base system. So, societal desirability and acceptance may call for lower-level technological systems.

As part of the Technology Monitor approach, we also describe the current state of digital twins in general, and we assess potential barriers to large-scale use of digital twins. We estimate that the first type of digital twins (level 1) emerged in the 1980s. From that time onwards, more advanced and higher-level digital twins emerged, each with their own pattern of development and diffusion. For level 4 digital twins, our analysis reveals that these twins are only applied in specific niche applications, for example in industrial processes. That means that level 4 digital twins are not applied (yet) on a large scale.

We also observe that most of the barriers to large-scale use are social factors rather than technological. Different actors need to collaborate to develop, build, implement, use, and maintain digital twins. The network formation just started and local networks are formed that adopt different solutions and hence standards, rules and laws regarding the proper use of digital twins are not yet established. The results are summarized in the next figure.



Core factors		Influencing factors	
1 Product performance		8 Knowledge of technology	
2 Product price		9 Knowledge of applications	
3 Production system		10 Employees and resources	
4 Complementary prod & services		11 Financial resources	
5 Actors & network formation		12 Macroeconomic and strategic aspects	
6 Customers		13 Sociocultural aspects	
7 Standards, rules and laws		14 Accidents and unexpected events	

The figure on the timeline shows when the level 4 digital twin was first explained and first introduced. The overview with (f)actors shows which actors or factors hamper large-scale diffusion. Red means that a factor is a full blockade for large-scale diffusion, orange means a factor is partly blocking, green means the factor is no longer blocking large-scale diffusion (or can even stimulate).

The recommendations from these findings are as follows:

- It is important to develop and share knowledge about applications of DTs.
- Potential customers need to be informed about potential applications of DTs.
- People working with DTs need training to prevent unwanted side-effects and accidents.
- Experiments in contained spaces are needed to observe and learn about accidents without major impact.
- A balance must be struck between what is cost-effective, strategic on the one hand and societally acceptable and desirable on the other hand. Finding this balance is part of political and societal embedding of digitalisation technology.
- Different actors that are required to collaborate for DT development and use, have to be aligned in networks.
- Standards, rules and laws are required to guide the development and application process.

Part II

The second part focuses on digital twins in the urban environment. Municipalities represent one type of stakeholders that play a role in the pattern of development and diffusion, as depicted in the figure.

To study how municipalities develop and apply digital twins, we zoom in, and look at how teams within municipal organisations work. We are grateful that our interviewees in Amsterdam, Breda, Den Bosch and Den Haag shared their experiences.

The application that municipalities are working on are summarized in the next table.

	Application	Use	Municipality
1	The DT includes detailed representations of buildings, roads, canals, vegetation, and underground infrastructures (e.g., the sewage system). There is a simulation of sunlight and shadow with pre-set weather conditions.	Policy forming and city planning; Involvement of citizens in evaluating city planning; Building and maintenance.	Amsterdam Breda Den Bosch Den Haag
2	The DT combines data about events, maintenance, and projects in the city, over time, to coordinate and minimise hindrance for traffic.	Planning events; Building and maintenance; Informing stakeholders.	Den Haag
3	Crowd and traffic control. Planned functionalities include real-time information feeds from sensors and real-time analysis, and providing automatic alerts if some safety limits are exceeded.	Events	Breda, Den Bosch Den Haag (Scheveningen)
4	Health and liveability using (e.g., noise and pollution sensors).	Liveability	Breda Den Bosch
5	Water and sewer system management for tracking water and sewage problems.	Problems	Breda Den Bosch

Development of a digital twin (DT) is a complex innovation process that cannot be represented as a simple innovation project. Our investigations revealed how the development and application of digital twins creates a tricky problem for municipal organisations. We observed that digital twins can be perceived differently by different stakeholder groups, and we noticed how their development and application is hampered by several sub-problems that in practice are highly interrelated.

Development of DTs in the municipalities starts for different reasons, the upcoming 'Omgevingswet', the need to carefully track crowds during COVID19 lock-downs, or as part of a larger digitalisation agenda. The start is usually a project with temporary funding. The result of that project is a plan, or a demo, all meant to arouse interest. But that does not lead to political embedding and long-term commitment which are required to fund subsequent efforts that embed the digital twin in the day-to-day operation and organisation of the municipal organisation. Instead of an internal network within the municipal organisation, many interviewees indicated that they collaborate with similar departments in other municipalities. These departments do understand each other and collaborate, but each of them faces problems forming a network within their own municipality. The type of networks formed around DT efforts are currently shaped to develop and explore rather than implement. There is a risk that complete fragmentation will emerge, when sharing and learning from each other's experiences across networks is limited.

We found ten aspects that are important when developing and implementing DTs in a municipality. Each of the municipalities that we interviewed performed well in some of these aspects while they struggled with other aspects. In the table we present recommendations using these aspects.

	Aspects	Description and recommendation
1	Political embedding	The DT development and experimental efforts need to be part of a political agenda, to ensure the commitment required for a long-term programme that will consist of many projects.
2	Organisational embedding	Implementing the use of DTs (and more broadly: the entire digitalisation) in the municipal organisation means that the current organisational structure and processes may have to fundamentally change. This is a major effort that requires long-term commitment.
3	Type of funding	Development and implementation cannot just be based on temporary project funding and organisation, it requires a structural budget and a permanent organisational embedding.
4	Internal network	It is important that those within the municipality involved with the development of DTs reach out to other in the municipal organization that may use the DTs. In this way the 'technology push' and 'grand visions' are re-directed towards demand-pull, meaning actual problems are addressed that are on the political agenda and that are important for citizens and organisations in the city.

	Aspects	Description and recommendation
5	External network	Many actors in municipalities involved with DTs have an external network with peers in other municipalities or other institutions (provinces for example). This external network is important for learning, aligning and standardising.
6	Understanding applications	Understanding applications means that potential applications are identified. An application involves identification of a few things: 1) A well-defined need or problem; 2) Relevant stakeholders; 3) A specific context. If DTs can (over time) fulfil the need (better than other solutions) then an application is identified.
7	Ordering of applications	The full list of applications represents a 'grand vision'. Dream big but start small. From the list, specific small-scale applications need to be selected that are relatively easy to implement, meaning that major organisational barriers are by-passed. If such applications allow a bit of experimentation and create visibility for other applications, if they involve modules or structures that can be re-used in subsequent applications, then they provide a fertile start.
8	Implementation	Start small and simple. Activities move through stages: from project, to pilot, to small-scale application, etc. It makes sense to work on a portfolio of activities.
9	Accessibility for different groups	Access can be scaled from developers, to internal users, to larger user groups.
10	Basic architecture standardisation	When different projects are planned, a standardised data architecture and other standards will have to be created to prevent local lock-ins. DTs are just one tool that should be applied as part of a larger infrastructure and portfolio of digitalisation tools and data management.

In the report, these ten aspects are used to create an audit with which municipal organisations can assess their own situation regarding digital twins.

Part III

The third part looks ahead. Our results indicate how municipalities are developing in different directions and that, in turn, inspired us to formulate three dimensions representing directions in which future developments regarding DTs can evolve. These dimensions are:

Directions of change	Effect on pattern of development and diffusion
1 The technological level of the DTs is increased.	Another (higher-level) technology is a new technology that can be tracked in a separate pattern.
2 The number of different applications is increased.	Another application means that the technology proceeds within an existing pattern.
3 The scale of using an actor network is increased.	Scaling up means that a technology shifts from small-scale to large-scale application.

Using these dimensions we could formulate a more general framework that can be used to explore future developments of a pattern of development and diffusion for a technology. This general framework can aid exploring the future of a technology and can thereby provide input for broader scenario-studies that STT typically creates.

Introduction

Digital twins are mentioned everywhere; it seems like a hype.

Business | The Gemini makers

Millions of things will soon have digital twins

From factories to cars to a range of consumer products

Dave Simonds

Jul 13th 2017

Share

Figure 1: Source: Digital twins in the City (rapport outline)(2022-09-21).docx - Google Docs

The term ‘digital twin’ is used to represent completely different things in practice. It is important to consider what digital twins actually are, or what they can be. This means that we need a definition and maybe even a classification of different types of digital twins. We will track historical developments to explore how the concept emerged, developed, and how it has been applied. To provide a perspective on how a digital twin can be applied now and in the future, we will focus on digital twins in a particular context.

This project focuses on digital twins in an urban environment. Digital twins refer to the combination of digital representations (referred to as the twin representation) of another, mostly real-world and physical, entity (referred to as the base system). Digital twins can be used for different purposes such as conducting experiments that are not possible with the base system in practice (i.e., what happens in case of calamities), predicting operational activities and necessary maintenance, or showing how the entity may evolve over time when its environment changes. The focus on an urban environment is logical, for example from the perspective of municipalities. Municipalities are in the midst of a digitalisation process. Creating digital twins of important assets in an urban environment allows municipalities to innovate and experiment without disturbing ongoing activities in the city. The project is conducted as part of the 'Technology Monitor', a tool that is developed for Stichting Toekomstbeeld der Techniek (STT). This Technology Monitor consists of three complementary parts: (1) A way to define a technological innovation; (2) A pattern of development and diffusion allowing the establishment of how the innovation emerged, developed and has been applied over time and to establish the current status of the innovation; (3) A framework to assess the current status of relevant actors and factors required for large-scale use and implementation of the innovation. In short, the three parts of the Technology Monitor describe historical developments up to the current state for a particular well-defined type of technological innovation (see Appendix 1 for a more elaborate description of the 'Technology Monitor').

The Technology Monitor was always meant to be complementary to the domain-specific approach often used by STT. The domain-specific approach focuses on a societal domain, like education or transport, and describes how societal and technological developments in combination may change these domains over time. Because of the timeframe with which STT looks ahead (ten years or more), considerable levels of uncertainty have to be faced. STT therefore often uses scenarios to describe possible future developments. The Technology Monitor is complementary to the domain-specific approach because it focuses on one technology and how that technology can be applied in multiple domains over time.

After discussing the Technology Monitor approach with the director of STT, Rudy van Belkom, the idea emerged to extend the Technology Monitor approach to also look ahead. Looking ahead is possible for example by describing options or scenarios of future developments regarding the technological innovation in focus. The Technology Monitor, once extended, will not only be complementary to, but can also become an integral part of, other studies by STT.

The Technology Monitor 2022 project is relevant for STT because it aims to extend the Technology Monitor approach to enable an exploration of future options or scenarios that fit other STT projects. The Technology Monitor 2022 project on digital twins in an urban environment is relevant for several STT members, such as those from municipalities. But other members may also benefit from exploring this fascinating development and application of digital technology.

The technology Monitor 2022 is divided into three work packages: (1) Digital Twin in General; (2) Digital Twins in an Urban Environment; and (3) A Look Ahead: Options for the Future. Each of these work packages will focus on one or more research questions (Exhibit 1).

Exhibit 1: Research questions

Digital Twins in General

1. What is a digital twin?
2. What is the (historical) pattern of development and diffusion of digital twins?
3. What is the current position of digital twins in the pattern of development and diffusion (in general)?
4. What are the general applications for digital twins?
5. What is the current status of actors and factors required for large-scale digital twin use (in general)?

Digital Twins in an Urban Environment

6. What are the specific applications of digital twins in an urban environment?
7. What is the current status of actors and factors required for large-scale digital twin use in an urban environment?

A Look Ahead: Options for the Future

8. What are the options for the future development and use of digital twins in an urban environment?
9. How can the technological functionalities provided by digital twins be embedded and made compatible with current and future policies, norms and values and the changing context of an urban environment?

Part I

Digital Twins in General

1

Introduction

In this chapter the concept of a digital twin (DT) is explored using the Technology Monitor approach. This means that we define what a digital twin is, track its historical pattern of development and diffusion and establish the current status of the innovation. The Technology Monitor approach will also be used to assess barriers to large-scale use and implementation of digital twins (DTs). We focus on the following research questions:

1. What is a digital twin?
2. What is the (historical) pattern of development and diffusion of digital twins?
3. What is the current position of digital twins in the pattern of development and diffusion (in general)?
4. What are the general applications for digital twins?
5. What is the current status of actors and factors required for large-scale digital twin use (in general)?

To answer these questions, we will use two methods: desk research and expert interviews. The desk research has two parts: a scientific literature research and a search of more general sources for experiences and practical information. The remainder of the chapter will be subdivided into sections that follow the research questions, starting with defining digital twins in section 1.2 up to assessing the current status of actors and factors required for large-scale diffusion in section 1.6.

Defining Digital Twins

Background and Definition: A Complex Concept that Evolves over Time

The Technology Monitor approach generally defines a technology by describing its technological principle, its functionality, and the main subsystem of the concept. At first sight, using this approach to define a digital twin seemed easy, because a formal definition had already been proposed by Grieves in 2002 (Grieves, 2015). We will start with Figure 2 which displays how Grieves perceived and defined the concept.

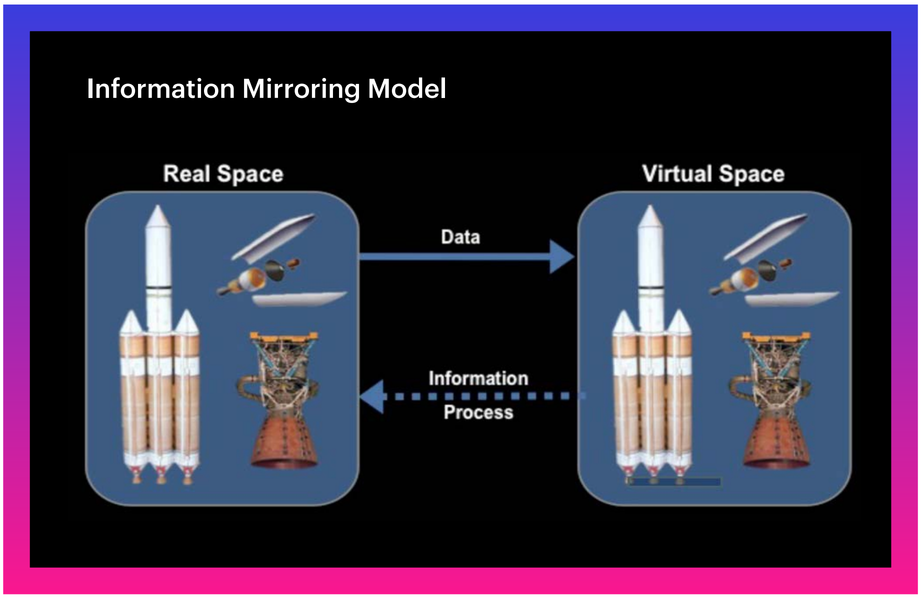


Figure 2: Digital twin as defined by Grieves (Grieves, 2015, p.2)

The digital twin concept model shown in Figure 2 contains three main parts: a) systems in Real Space, b) virtual systems in Virtual Space, and c) the connections of data and information that ties the virtual and real systems together in both directions. The first tier of subsystems are listed. Some of the main aspects of the technological principle are also presented because 'digital' refers to the principle that is applied to make half of the twins. We adopt the nomenclature of 'base system' instead of 'real system' to account for the fact that the original system being twinned could also be virtual instead of physical, such as a piece of software. Instead of 'virtual system' we use the term 'twin representation' to refer to the digital counterpart of the base system. This highlights the fact that it is integrally linked to the base system, rather than a standalone virtual system of some kind. Our formal definition is presented below.

> A digital twin (DT) is a tool for the development and control (both automatic and human) of base systems, including individual products, systems of multiple products, and multi-domain environments such as urban areas. Firstly, a DT consists of a detailed twin representation of a system. Secondly, data connections from the base product or system to the twin representation that can be used to transfer data that in turn can be used, for example, to conduct testing with the twin representation. Thirdly, data connections from the twin representation back to the base system that can be used, for example, for control.

This definition basically covers the three aspects of the 'Technology Monitor' definition: (1) The functionality (the definition refers to two functionalities, testing and control); (2) The technological principle (the twin representation and data connections refer to computer principles) and (3) The first tier of subsystems (twin representation, base system, connections both ways). Each of these aspects can be elaborated, and more detailed subsystems, more functionalities and more detailed technological principles can be described (see Exhibit 2).

Exhibit 2: Functionalities, technologies and sub systems that are often mentioned for digital twins

Possible functionalities of the digital twin:
- A digital twin acts as an automatic control system on (at least) short time scales (example: data comes in of unexpected traffic situation, digital twin data linkage passes the data to the model, the model indicates what action to take to stabilise situation, action is automatically sent back to base system vs. data display shows situation, human interprets and analyses the data and then takes appropriate action)
- A digital twin acts as a virtual sandbox to inform human decision-making on long time scales (Long-term forecasting, scenario analysis, contingency planning)
- A digital twin acts as an aggregated display of data from the base system (This data display may not be raw, but could be processed in real time to highlight important information to assist and augment human decision-making)
- A digital twin acts as a record of the history of the base system.

Technological principle(s) of the digital twin:
- Digital collection of real-world information (sensor technology)
- Digital storage of real-world information (storage technology)
- Digital transmission of real-world information (digital communication)
- Digital processing and simulation of real-world information (computers)

Possible subsystems of the digital twin:
- Base system
- Digital two-way data link (hardware)
- Digital data storage (hardware)
- Human-readable data display (hardware & software)
- Digital modelling (hardware & software)
- Human-accessible control interface (hardware & software)

Our definition means that DTs are more than just detailed computer representations or dashboard displays of real-world data. If a dashboard is created to control the railway system, that is not a digital twin because the system is not copied into a twin version but rather the base system is monitored closely using a dashboard.

As an illustrative example, let us imagine a DT of a modern car (see Figure 3).

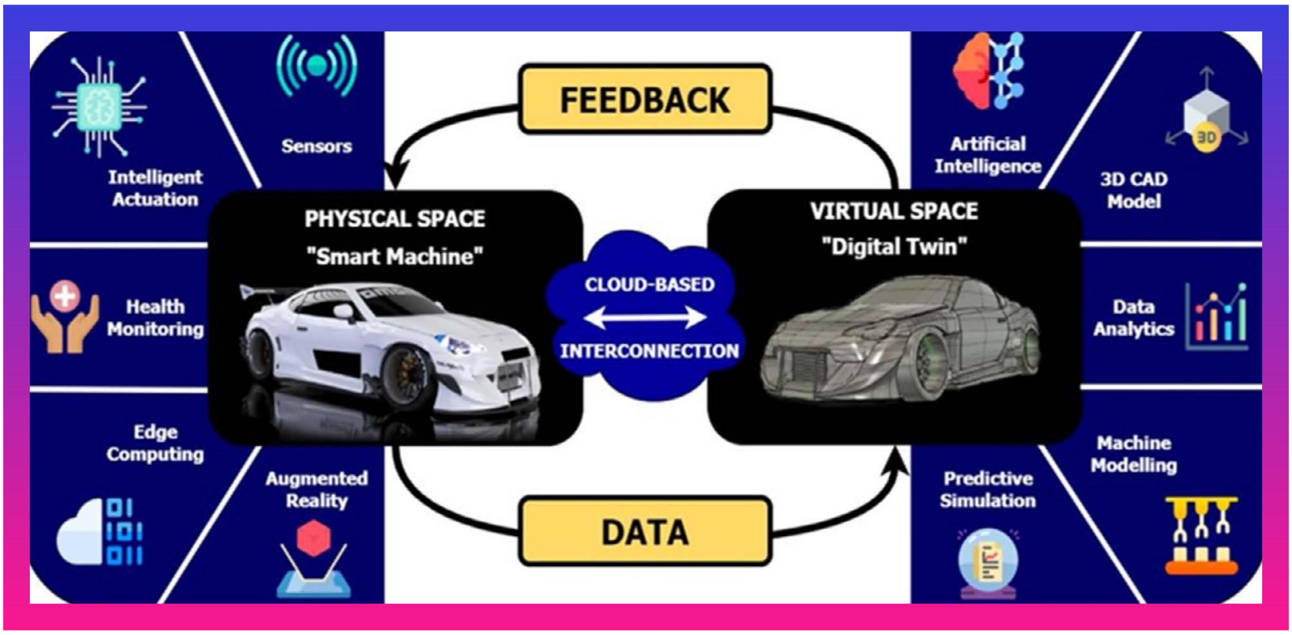


Figure 3: a car and its digital twin (source: https://encyclopedia.pub/entry/25054)

The detailed twin representation of the car and all its parts already exists prior to production, and can be used to inspect the product as it was designed with high accuracy. This is the level of a twin representation of a particular physical car. The representation is then augmented with suitable system models of the car components. Based on these models, we can now run virtual tests on changes of parts or settings, possible damage scenarios, and their simulated long-term effects on safety, performance, or comfort. This is the level of a system simulation of the particular physical car. This representation is then linked to various sensors and other data sources (odometer, engine controller microchip, emission sensors, etc.) in the physical car via a data link, and aggregated together with the computer representation to provide a live view of the details and state of the car. This data can then be fed into the simulation models for high-frequency monitoring, analysis, and simulation of the car's performance. This is the level of an integrated analysis dashboard of a particular physical car. Lastly, we have a data link from the twin representation and simulations back to the systems of the car, allowing the base system to be automatically controlled and optimised remotely to some degree. This completes the digital twin.

Issues with definitions and a solution

1. There are many different definitions (Van der Valk et al., 2020; Jones et al., 2020). So, 'digital twin' can mean different things.

2. Some systems do meet our definition but are not referred to as digital twins (see Exhibit 3). So, some concepts fall under our definition but have different names.

3. The definition does not match with the digital twins that are described, tested and used in practice. In practice there is a kind of evolution of the concept.

Exhibit 3: Systems that meet our definition but are not referred to as digital twins

Applications that are not explicitly labelled as digital twins, but could be seen as such/can be argued that all of these can be seen as digital twins or 'primitive' digital twins when looking back in the future:
- Google Earth / virtual 3D maps
- Virtual 3D car/vehicle displays
- Building management systems

In general terms, anything virtual that can be used in lieu of a particular base system, system or environment to display, inspect, test, develop, manage the real thing.

To resolve the three issues, we will focus on the evolution of the concept. It is remarkable that actual applications of digital twins that meet our definition have hardly been publicly recorded. Instead, most of the digital twins in operation seem to satisfy a simplified version of the concept. We assume that the technology, its functionalities and main subsystems, have been evolving in a logical sequence. This sequence inspired us to formulate a multi-level definition. At each subsequent level of the definition, new principles, functionalities, and components are added. The previously outlined definition by Grieves fits our level 4, while the lower levels define the type of digital twin that we can actually see in practice and seem to precede the level 4 definition. In Table 1, those four levels are described, each with their technological principle, functionality and first tier of subsystems. For each of the levels we provide an example.

Table 1: Four levels to distinguish different types of digital twins

Level	Description	Principle	Functionality	Subsystems	Example
1	There is a base system and a digital representation of that system. The two are not directly connected.	Virtual modelling	Recording, displaying, (re)designing	Data storage, computer, rendering software	CAD-representation of the design of a base system that can be developed or already exists and then can be easily redesigned.
2	There is a base system and a digital representation that simulates some key processes or mechanisms of that system. The two are not directly connected.	Virtual simulation	Testing, forecasting	Simulation software	Detailed twin representation of a base system with operational simulations that can be virtually tested and analysed.
3	There is a base system and a digital representation that simulates some key processes or mechanisms of that system. The two are connected one-way with information flowing from the base system to the virtual representation.	Digital commu-nication, sensors, AI	Tracking in real time	Data connectors, sensors, AI software	Detailed twin representation of a base system with operational simulations and real-time data analytics to optimise maintenance and aid human control.
4	There is a base system and a digital representation that simulates some key processes or mechanisms of that system. The two are connected two-way.	Controller technology, machine learning	Autonomous control in real time	Machine Learning software, controllers	Detailed twin representation of a base system with operational simulations, real-time data analytics, and control feedback to optimise performance in real time.

The notion that, in practice, digital twins seemed to evolve towards the ultimate definition or level as provided by Grieves (2015) is interesting. Digital twin refers to a set of technologies that over time evolved from one technology (level 1) to other technologies (levels 2 and 3) until the technology emerged that meets the requirements of the (level 4) definition by Grieves (2015).

Later on, in the work package that looks at cases of digital twin applications, we will see that this evolution is neither inevitable nor societally desirable, in some cases. Or, to put it differently, being able to create a high-level digital twin doesn't mean we should. Especially when applying digital twins in an urban environment, it might be important that the results from the digital twin are not automatically fed back into the base system but are fed back through a person or authority that has the mandate to check and implement the suggested action. Similarly, not for all types of digital twins is it required that measurements (from sensors or any automatic observation) are automatically and instantaneously fed into the digital twin (a mechanism that is part of a level 3 digital twin). In some cases, the data can be entered after it is checked by a person, and hence it enters the digital twin after a filter and with a delay. Other types of personal interventions or checks, in a system that may technically operate autonomously, may be desirable.

While the digital twin technology evolved technically (in terms of the levels covered), subsystems were added and new functionalities became possible. As a result, over time, new applications emerged. In the next section we will elaborate on these applications.

While the digital twin technology evolved technically (in terms of the levels covered), subsystems were added and new functionalities became possible.

General Applications of Digital Twins

Applications that have been envisioned since the first occurrences of digital twin as a term, have focused on virtual models of physical systems to allow study, testing and design when it would otherwise be infeasible or too expensive. This includes uses such as models of human joint movement for ergonomic design, and the design and lifecycle tracking of components or systems in the aerospace industry (Hu et al., 2021). However, the applications envisioned for fully fledged digital twins focus on optimization of development and maintenance, system analysis and autonomous control. A full digital twin of a system would entail detailed tracking of its properties in near-real-time, detailed virtual testing to validate any planned changes before implementation, anticipation and detection of problems in the system allowing reactive and proactive control and optimised maintenance, the elucidation of hidden dynamics between subsystems or components, scenario analysis for risk control, and ease of restoration in case of damage or loss. Different envisioned applications by function can be categorised as follows:

1. **Design representation application:**
   Virtual representation and backup (level 1)
2. **Design simulation application:**
   Simulation, systems analysis and testing of (future) operation, scenario analysis (level 2)
3. **Operation monitor application:**
   Virtual monitoring and recording of system behaviour in operation, including virtual back-ups and problem detection and anticipation (level 3)
4. **Operation control application:**
   Automatic control during operation. (level 4)

Practically visible applications are present at various levels of implementation across different sectors. To summarise these, a table of realised applications based on review and defined sectors in Singh et al (2022) is provided. Following Singh et al. (2022) we order the applications per sector. For each sector we give examples of applications with an estimation of what level of the DT definition they meet (column 3) and summarise the highest implemented level per sector (column 2).

Table 2: Applications of digital twins in different sectors

Sector	Level	Examples
Aerospace and Aeronautics	Level 2	- 2019: (Level 2) Realised DT of a rocket engine by NASA with real simulations for design optimisation and pre-flight testing.
Manufacturing	Level 3	- 2015: (Level 3) Realised DT of design & production system used by Maserati for vehicle design & production system optimisation. - 2021: (Level 3) Practical demonstration of DT of collaborative human-robot workstation for linear actuator production.
Healthcare and Medicine	Level 2	- 2018: (Level 2) Realised DT of radiology department in Mater Hospital in Dublin, Ireland for operations and layout optimisation. - 2018: (Level 2) Realised DT of a patient’s heart for virtual testing of advanced pacemaker technology. - 2019: (Level 2) Practical demonstration of DT of Alzheimer’s patients as control/placebo subjects for disease progression study.

Sector	Level	Examples
Power Generation & Energy	Level 3	- 2016: (Level 3) Realised DT by GE of a wind farm in Eastern U.S. to optimise layout and turbine choice. - 2016: (Level 3) GE offering DT services for wind farms with real-time data analytics. - 2017: (Level 3) Realised DT by Siemens of the national power transmission grid in Finland with real-time data analytics. - 2021: (Level 3) Realised DT by DNV of a wind farm in the U.S. detected a production anomaly that was diagnosed to result from an incorrect setting. - 2021: (Level 3) Realised DT trial by Kongsberg Digital of the national power transmission grid in Norway with real-time data analytics.
Automotive	Level 4	- 2019: (Level 3) Realised DT for Mercedes-AMG Petronas Motorsport F1 team using real-time data collection from a racing car and using virtual environments to simulate design changes for optimisation. - 2020: (Level 3-4) Realised DT of every Tesla car, using data collection, virtual simulation, and remote optimisation of individual vehicles. - 2020: (Level 2) Realised DT of a ŠKODA AUTO component plant in Vrchlabí, Czechia for operations and layout optimisation.
Oil and Gas	Level 4	- 2018: (Level 3) Realised DTs of BP North Sea oil and gas plants to monitor and optimise production by real-time data analysis and simulation. - 2020: (Level 4) Realised DT of Royal Dutch Shell gas processing hub in Aukra, Norway using real-time data monitoring, simulation, and real-time automatic control to optimise LNG production and maintenance.
Smart City	Level 3	- 2020: (Level 3) Realised DTs by AVEVA in Carson City, Nevada, U.S., for real-time monitoring of city infrastructure including water, waste management, transportation, and renewable power systems with AI-based diagnostics. - 2018: (Level 2) Realised DT 'Virtual Singapore' of Singapore urban environment for planning and virtual experimentation. - 2022: (Level 3) Realised DT by Cityzenith in Las Vegas, Nevada, U.S., for real-time display and analysis of IoT data in and around the airport.
Mining	Level 3	- 2018: (Level 3) Realised DTs for mining equipment of Anglo American Plc for both maintenance monitoring and performance simulation.
Maritime and Shipping	Level 2	- 2019: (Level 2) Realised DT by DNV for Saipem for planning and maintenance management of large crane vessels.
Retail	Level 3	- 2018: (Level 2) Realised DTs of Intermarché supermarkets in France for monitoring and analysing data from IoT-enabled shelves and sales systems and experimenting with store layouts before implementation.

It is clear that digital twins are already widely adopted in practice across different sectors. However, the level of implementation across most sectors conforms to levels 2 and 3 as specified in our definition, namely because most implementations lack the aspect of autonomous control, with a human included in the decision chain for all actions. Most implementations focus on a virtual model for both near-real-time monitoring, and testing to aid future planning. Practical examples of the fullest implementation at level 4 that include autonomous control do exist in both the automotive and energy sectors. Examples of practical implementations of DTs in agriculture, education, construction and Insurance & Finance are so far lacking, but proposed implementations do exist.

This section shows that development and application of digital twins is sector-specific. It is important to look at the sectors that are ahead in applying the highest-level digital twins, because these applications provide a perspective on what might be possible in the future in other sectors. However, sectors not applying (the highest level of) digital twins are not necessarily lagging behind or less sophisticated. It might be that in some sectors the functionality of digital twins is not needed or is not desirable societally. In that case, such sectors reveal their sophistication by not using (the highest level) digital twins for a good reason. In the exhibit below an example of a level 4 digital twin is described.

Exhibit 4: A level 4 digital twin in the oil and gas industry (Source: an interview with Saskia Vlaar)

Types of digital twins A digital twin of a refinery can be as simple as a basic 3D model of the physical dimensions, and as complex as including simulations, live data streams, and control connections to the physical object.

The physical object and its digital twin: who is first? In some cases the digital part precedes the physical part (design before construction). In other cases the digital part is created later to mimic the physical part.

Multi-applicability and the specialisation trap A digital twin of a refinery can involve real-time information feeds, simulations of processes and control loops back to the (physical) refinery. This however represents a highly specialised digital twin that may be difficult to reuse or adapt to other use cases, presenting a possible specialisation trap. The specialisation trap means that in the digital twin so much detail is added that the twin is hardly usable as a building block for other types of applications. So, higher level digital twins may come with a kind of specialisation that hampers the use of the DT in other applications. Specialisation hampers multi-applicability.

Multiple twins of the same physical entity Organisations sometimes need multiple digital twins: for example one fully operational digital twin, one digital twin as a back-up, and one digital twin used to develop new aspects (that later on may be put into use in the full operational twin). If the digital and physical parts are intimately connected, organisations may also need multiple physical representations next to the multiple digital representations.

Is there some kind of sequence of applications? An application is using digital twins to design physical things, and then using the design data to construct and later on modify physical things. An example of application evolution is the development of multiple applications into separate digital twins based on the same initial coordinate set or other relevant base data. A good digital twin consists of building blocks and should be developed as something that can be reused and expanded into other applications.

The Pattern of Development and Diffusion of Digital Twins

After defining 4 levels of digital twins, each of which can be seen as a separate technology (because their functionalities, their technological principle of working and their subsystems differ) we can describe four patterns of development and diffusion, one for each level. The digital twins that function on levels 1-3 are currently applied as a standard technology on a fairly large-scale in multiple sectors. Level 1 digital twins, for example Computer Aided Design, were already used on a large scale in the 1980s. This means that level 1-3 digital twins are in the stabilisation phase (see Exhibit 5).

Exhibit 5: *Introduction of AutoCAD, a level 1 digital twin application in MS-DOS.*

When were the first AutoCAD type of computer programmes introduced?
The first version of AutoCAD, which is one of the most popular computer-aided design (CAD) programmes, was introduced in December 1982 by Autodesk. It was developed for personal computers running on the MS-DOS operating system, which was the dominant operating system at the time. The initial version of AutoCAD had a limited set of features compared with current versions, but it was still a significant advancement for the CAD industry at the time. Since then, AutoCAD has gone through many updates and improvements, and it is still widely used today by architects, engineers, and other professionals in various fields.
(https://chat.openai.com/ (2023-03-31).

Digital twins on level 4 are more rarer as they are only applied in specific market niches in selected sectors. We therefore conclude that they are still in the adaptation phase.

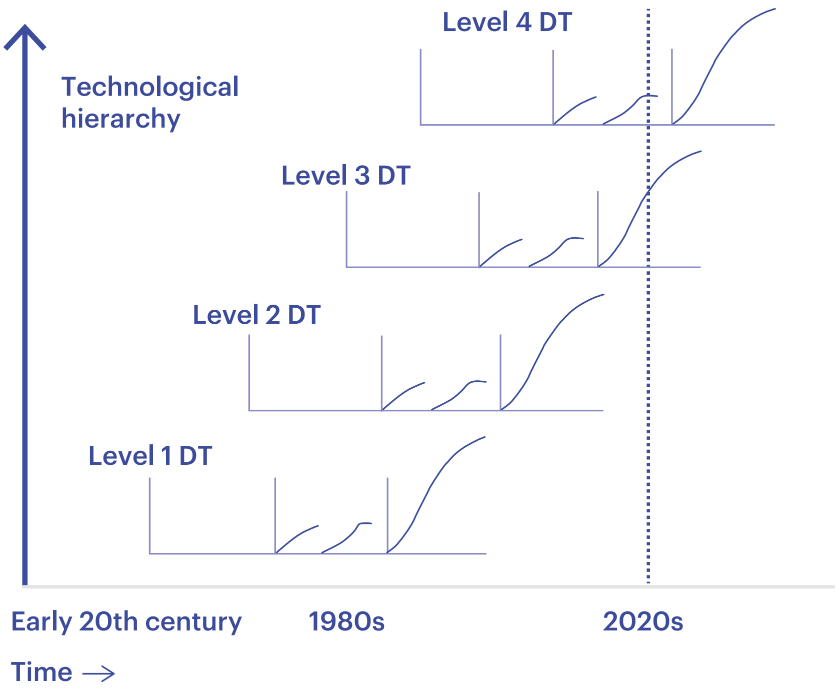


Figure 4: Pattern of development and diffusion four different levels of digital twins

If we focus on level 4, we can see that digital twins on level 4 are now applied in market niches, although the concept was defined formally in 2002 (see Figure 5). We claim that digital twin technology at level 4 is still in the adaptation phase. That seems counterintuitive because the term is everywhere and all types of organisations are working on digital twins.

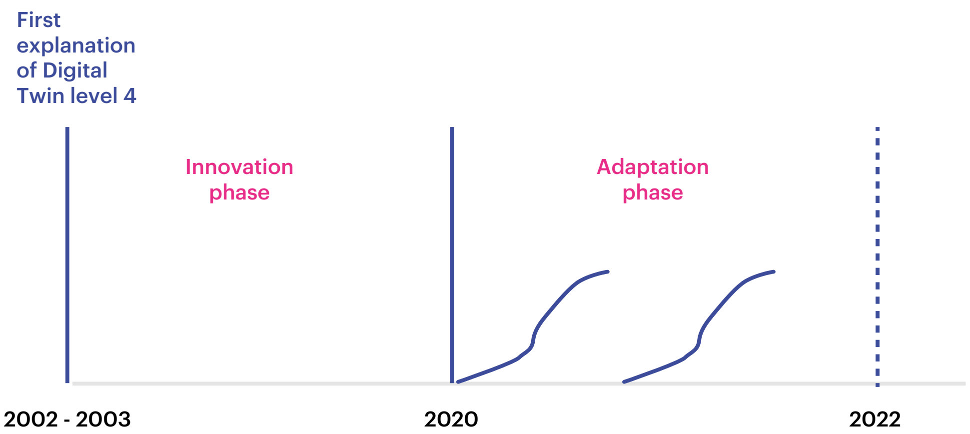


Figure 5: Pattern of development and diffusion of digital twins (level 4)

Indeed if we look at the use of the search term, the number of articles and citations we see both develop exponentially after 2015. However, our definition of digital twin refers to an advanced system that includes connections in both ways between the base system and the twin representation. We found just two market niche applications of such systems, an indication that the level 4 systems are still in the adaptation phase.

If we look at digital twins in general, we can see that the use of 'Digital Twin' as a search term has increased considerably after 2015 (See Figure 6).

Figure 6: Relative number of uses of the term 'Digital Twin' as a search term in Google

If we look at the number of publications with the term 'Digital Twin' in the title, and at their citations (see Figure 7), we find two similar trends.

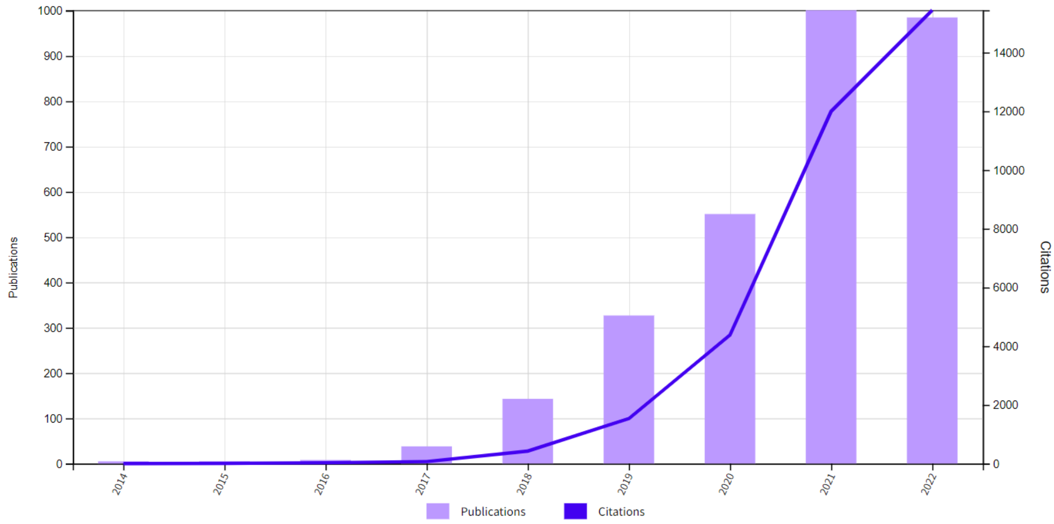


Figure 7: Relative number of articles with 'Digital Twin' in title and the number of citations of such articles

Conditions

We considered the seven core factors and seven explanatory influencing factors for the most complete implementation of a digital twin (DT), as defined by level 4 of our multi-level definition. The general list of core and influencing factors are introduced and described in Appendix 1.3. In Table 3 we give a quick overview of the status of the core and influencing factors for DT (level 4). In the left column are the core factors, representing aspects of the Technology Innovation System that needs to be in place and compatible before large-scale diffusion and implementation is possible. We have applied a traffic light system to indicate the status of these core factors: green means that the status of the core factors does not hamper large-scale diffusion of level 4 digital twins (DTs); orange means part of the factor is in place and another part not; red means major parts of the factors are not in place and hence represent a barrier to large-scale diffusion and implementation of level 4 digital twins (DTs).

Table 3: Core factors and influencing factors hindering or supporting large scale diffusion of level 4 digital twins

Core factors	Influencing factors
1 Product performance	8 Knowledge of technology
2 Product price	9 Knowledge of applications
3 Production system	10 Employees and resources
4 Complementary prod & services	11 Financial resources
5 Actors & network formation	12 Macroeconomic and strategic aspects
6 Customers	13 Sociocultural aspects
7 Standards, rules and laws	14 Accidents and unexpected events

A core factor is green when that factor is not a barrier and all of the influencing factors positively affect the core factor. An influencing factor is green when it has a positive effect on all core factors it is affecting.

The main barriers to large-scale diffusion of digital twins are the lack of a complete actor network and the lack of relevant standards, rules, and laws. The statuses of these two factors are intimately related: to align all relevant stakeholders and to have them collaborate requires standards and rules that are set and agreed on, so actors know how to collaborate and create compatible parts that together make up the entire system. The core factor 'Customers' is partially in place and partially incomplete, hence the orange colour. The status of the factor is explained by the fact that many customers, be they companies or other types of organisations show interest in the technology, and start experimenting and piloting with digital twins. However, the knowledge and experience to fully integrate the DTs into the operational processes, redesign those processes accordingly and thereby benefit from digital twins, is limited.

The status of some of the influencing factors explains why barriers are visible in the Technology Innovation System for digital twins. The knowledge of how to apply and integrate digital twins and hence the 'knowledge of applications' is limited. There is a lack of employees with the knowledge and competences to build and implement DTs. Macro-economic and strategic aspects as well as sociocultural aspects sometimes influence (hamper) customers.

In order to make the relationships between the influencing and the core factors visible, we present them in a table (see Appendix 2).

Customers do not know exactly what they want when requesting or showing interest in DTs, which limits development of demand.

It is interesting to notice a few issues after studying the factors. Our analysis implies that social conditions are blocking the development and diffusion of DTs more than technical conditions. In the overall social sphere, a dominant aspect is siloing of knowledge and actor networks. The realisation of DTs requires cross-institutional and cross-disciplinary contact and communication, but this is not a necessity for most technologies, and as such is not the norm. Lack of common understanding (including a common definition) limits network formation. There are also networks with knowledge relevant to DTs with no awareness of their relevance to DTs because they use an entirely different terminology, such as building management systems, or risk management systems in finance.

Customers do not know exactly what they want when requesting or showing interest in DTs, which limits development of demand. This is due to limited knowledge and level of education on the technology.

Institutions relevant to digital twins have a lack of or conflicting standards arising from a lack of knowledge of applications, sociocultural aspects such as siloing, and risk fundamental conflicts of interest in developing DTs if siloing is not overcome.

Conclusions

Following the work of Grieves (2015) we define a digital twin as a base system and a twin representation of that system. The twin is connected in both ways: from the twin representation to the base system and back. The subsystems of the twin, its technological principles and its potential functionalities are all described in section 1.2).

We found that many current applications of digital twins do not fulfil this definition completely. Despite this, we found a logical sequence for how the concept of the digital twin evolves in practice depending on the addition of components and functionalities, and that the observed applications conform to this scheme. This is expressed as four levels of implementation.

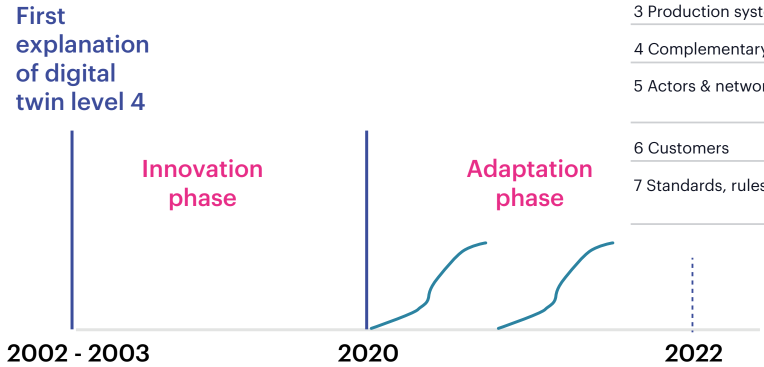
Level	Description
1	There is a base system and a twin representation of that system. The two are not directly connected.
2	There is a base system and a twin representation that simulates some key processes or mechanisms of that system. The two are not directly connected.
3	There is a base system and a twin representation that simulates some key processes or mechanisms of that system. The two are connected one-way from the base system towards the twin representation.
4	There is a base system and a twin representation that simulates some key processes or mechanisms of that system. The two are connected both ways. That from the base system to the twin representation is usually a data-feed. The other is usually a control feed.

(*) This is a short version of Table 1 provided before

We note that each of the levels could be considered a fixed technological unit with its own pattern of development and diffusion, but these are logically linked to one another.

Based on our full definition, we establish the following pattern, including the found conditions and barriers to large scale diffusion:

> Our analysis implies that social conditions are blocking the development and diffusion of DTs more than technical conditions. The social conditions representing barriers are 'actors and network formation', 'standards, rules and laws', and to a lesser extent 'customers'. The influencing conditions or causes of these barriers were explored in detail, but overall, again, market aspects, socio-cultural and macro-economic or strategic aspects seem more important than practical aspects, like knowledge of technology or financial resources.



1 Product performance	8 Knowledge of technology
2 Product price	9 Knowledge of applications
3 Production system	10 Employees and resources
4 Complementary prod & services	11 Financial resources
5 Actors & network formation	12 Macroeconomic and strategic aspects
6 Customers	13 Sociocultural aspects
7 Standards, rules and laws	14 Accidents and unexpected events

Figure 8: The pattern of development and diffusion and the current conditions for level 4 digital twins

We observed that digital twins are a multi-applicable technology over multiple sectors (or application domains), with differences in the number of available examples and levels of implementation per sector. This highlights the need for awareness of sector-specific conditions and barriers to implementation of digital twins.

To address the barriers to large-scale diffusion, and to take into account the sector-specific nature of the barriers, we make the following general recommendations:

1. Form a stakeholder overview per sector. Form an association per sector to lead towards an aligning process within that sector. Across sectors, multiple associations could align the most basic aspects across sectors.
2. Provide a (safe) space with limited regulation in which to conduct pilots. In these spaces, mistakes and accidents can be contained and manageable.
3. Conduct pilots and share the results across relevant stakeholders per sector. This will limit duplication and hence implies careful use of resources.
4. If processes of implementation are shared, stakeholders can easily find out how to implement a twin. By sharing information they can learn from each other what the possible results could be.
5. In pilots, do not just address technological aspects (these were considered not to be the main barrier to large-scale diffusion) but bring together stakeholders in a network and involve them in piloting.
6. Set standards (at least per sector or application) so similar actors can use each other's twins as a starting point. Currently, twins are created in different environments and this limits re-use.
7. Direct the development and diffusion in societally desirable directions. Include ethical aspects and socio-cultural aspects in order to safeguard a responsible use of digital twins. Stakeholders should know, for example, what the twin representation is and what the base system is. Stakeholders should also know that advice generated by a twin representation should not just be copied to the base system without a check for responsible use.
8. To increase the knowledge among potential customers using digital twins, education (e.g., on-line courses etc.), demos, illustrative projects, should be available.

Part II

Digital Twins in an Urban Environment

2

Introduction

To study digital twins in an urban environment, we decided to adopt a multiple case-study approach. We study how digital twins have been developed and implemented in a few municipalities. This allows us to compare innovation processes across distinct municipalities. We thereby move from the more generic level of the pattern of development and diffusion to the more specific level of innovation processes (mostly organised as programmes of related projects) in specific locations. We zoom in, and that allows us to compare different cases. The digital twins in the municipalities under study differed in terms of maturity, but all the activities started relatively recently (after 2019).

For further inspiration and to put our municipal cases into perspective, we added two extra interviews. Firstly, an interview zooming in on the use of digital twins to simulate our homes. Secondly, an interview concerning the use of a digital twin in the *Noordzeekanaalgebied*, a large area in the province of South Holland.

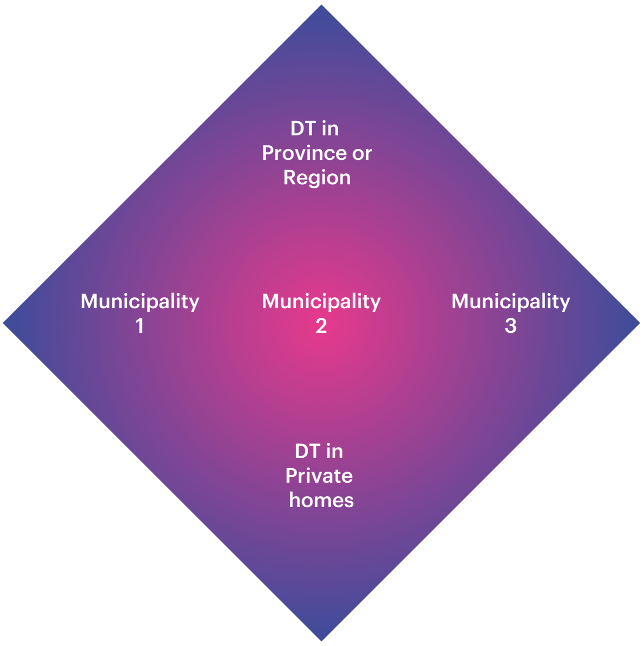


Figure 9: An overview of the five interviews about digital twins

In studying the three municipal cases, interviews are divided into four main parts:

1. **The digital twin and its use:** In this part, we discuss the type of digital twin (using the four levels as described in chapter 2) and the type of applications developed, implemented or envisioned.
2. **Process and problems faced:** In this part, the focus is on the process by which the DT-development was triggered, developed, implemented and used. Furthermore, this part discusses barriers confronted during this process.
3. **Results:** This part describes the result of implementing the DT in practice. This may for example refer to the scale and scope of use of the digital twin, and possible effects thereof.
4. **Future vision:** The final part reflects the direction in which DT development and use is moving. This part summarises the interviewees' vision regarding DT development and use in their municipality in the future.

To address these topics we used two sources of information for each case: a search of public information sources, and interviews with people involved with the development, implementation and use of DTs in an urban environment.

Case Descriptions

In this section we describe the specifics of DT development and use in Amsterdam, Breda, Den Bosch, and Den Haag.

Municipality Amsterdam: ‘3D Amsterdam’

Based on an interview with Jan Duffhues, Wietse Balster and Bruno Ávila Eça de Matos.

The digital twin and its use

‘3D Amsterdam’ is a public web-based digital representation of Amsterdam, in development and used within the department Ruimte en Duurzaamheid by Team Beeld & Data. The digital twin (DT) is considered first and foremost a central source of 3D information for static objects and infrastructure within the urban space.

Figure 10: 3D Amsterdam (birds-eye view of area with a small overview map) (source: https://3d.amsterdam.nl/#122127.59,488036.35,1143.55,56.00,344.51,0.00)

The DT includes detailed representations of buildings, roads, canals, vegetation, and underground plumbing. These are complemented by airborne image layers, and zoning and planning maps over time. There is rudimentary simulation of sunlight and shadow with pre-set weather conditions. The DT is currently used to various degrees by different actors who rely on accurate 3D information, such as architects working on design projects in the city, and by engineers working on construction and maintenance, for

'80 Euro en een week later hadden wij precies hetzelfde wat dat bedrijf uit Londen ons voor heel veel geld wilde verkopen. Toen hebben we mandaat gekregen, jongens, ga dit uitwerken.'
Wietse Balster, Amsterdam

(80 Euro and a week later we had exactly the same as what the company in London wanted to sell us for a lot of money. Then we got the mandate, boys go work this out.)

whom the DT is a fully fledged tool for their needs. For others such as planners, the DT is currently at the stage of an interesting demo, but not yet practically integrated into their working processes.

Planned functionalities include display of underground cables, photo-textures for buildings, a method for updating single 3D objects and personal log-in for accessing a private 3D environment for showing non-public data. For simulation functionality, traffic simulations and crowd management functionality may be included in the future. This will be to test planned changes and their effects on the urban environment before implementation.

The DT is planned to be used by any instance that relies on a 'single point of truth' for 3D information about the city. This 3D information can be used by actors within the municipality, external actors, and the public. For the latter two, the development is focused on open standards and accessibility. The ambition is that the DT will become a tool for both policymaking and design processes within the city, and to help communicate information about the physical state of the city to the public more effectively.

Process and problems faced

The project was launched in October 2019. The decision to launch was taken within the Team *Beeld & Data* triggered by the upcoming adoption of the *Omgevingswet* legislation in the Netherlands. After attending a presentation of a company creating such 3D-maps for cities, one of our interviewees explained that they instantly realised they had the knowledge to do this themselves, much cheaper and quicker. The team also noticed that external data tools can be highly inflexible despite their potential benefits. The DT has been developed internally based on open-source development, including collaboration with Rotterdam and a DT project '3D Utrecht' with Utrecht. The advantage of doing this internally, in collaboration with network partners was obvious: it was cheaper, could be re-used by other municipalities, and the tool could be made public without having to pay fees per use (as is the case with digital twins developed by some external companies). Interestingly, the original reason to start developing the digital twin, the *Omgevingswet* is still not adopted. Yet, the versatility of the tool enables other applications and user groups.

The project has involved stakeholders from other municipalities, namely data-oriented teams from Utrecht, Rotterdam, and the provinces of Flevoland and Utrecht. Together with these, there now exists a collaborative scrum team for further development, including the ambition of setting the standards and collecting data for a 'Netherlands 3D'.

The developers report that there are both political, organisational and technical barriers to use of the DT. Organisationally, there are the limitations of funding and knowledge of applications by potential users. The 'internal users' are working in the various domains of the municipality: the physical, social or public domain. These domains have an assignment ('*opgave*') to create tools that would later facilitate a more efficient operation across domains. However, their way of funding hampers investment in common tools.

Politically, there are also limitations. The DT is currently not an explicit part of the political ambition and programme of Amsterdam. This ambition is formulated in the '*coalitieakkoord*', a political programme for the next period of four years. In that programme, digitalisation and digital transformation are mentioned in general but it does not directly specify how DTs can be used by the domains and how their development can be funded. This means that the development and implementation of the DT is reliant on uncertain and insufficient project-based funding. This project-based funding can be either internal (from the physical domain) or external (for example from subsidies from the *Ministerie van Binnenlandse Zaken en Koninkrijksrelaties* (BZK) or from the EU) but a dedicated organisation and more permanent funding to support it, is altogether lacking. In terms of user knowledge, there is limited knowledge within the different departments and teams in the city about what exactly they could do with the DT, and there are? few resources for embedding it in existing processes. On a technical level, there are limitations for the end-users due to the large quantities of data being processed and rendered. In particular, the DT is not yet accessible on mobile phones and may perform poorly depending on the hardware and networks of end-users. (However, this too is one of the improvements to be made in 2023, taking away a great part of technical limitations.)

Results

The process so far has resulted in a DT that is practically implemented, accessible to the public, and in active use by both internal and external actors. So far, the team reports that the DT is in active use with architects and engineers involved in projects within the city, but there are still barriers to be overcome for more extensive use within the city organisation itself. Despite these barriers, development of the DT has been rapid: The first application was at the end of 2019 while development started at the end of 2018. That is very quick. A stated success so far is being able to implement already existing standards and to develop useful new standards for 3D information and implement these through the DT, which is expected to have high long-term value.

Future vision

Initially, our interviewees were against high-level DTs because what is most technologically advanced is not always needed or desirable societally. Later on, during the interview, it was indicated that for some use cases there could be higher-level DTs. For instance level 3 DTs for environmental monitoring, and level 4 DTs might make sense for traffic lights because of the complexity of the operation and the speed at which results are required (human operators cannot deal with that).

The interviewees do not expect a full simulation and integration of different use-cases (applications) of the 3D City Model as a DT. In contrast, it is expected there will be standardised data that can be added in layers for different DTs. Integration is possible in a federated way, meaning that multiple DTs will exist for instance on the basis of a common data architecture.

Some potential user groups in Amsterdam do see the DT as an interesting demo (e.g., planners) whereas other user groups can more easily see its added value in practical use (e.g., engineers). So, a kind of logical order of user-groups may emerge. The department working on 3D Amsterdam has a vision to develop one main application and make that part of 'Netherlands 3D' by extending the same application to other municipalities in the Netherlands. Sharing open source tools with others is the key philosophy of this vision.

Municipalities Breda and Den Bosch: Multiple Developments

Based on an interview with Margriet Heessels and Rob Nijkens

The digital twin and its use

Breda and Den Bosch have multiple pilots with digital twins (DTs) and similar applications in a variety of domains including crowd and traffic control, health and liveability, urban planning, and sewer system management. Rather than considering their developments as a single central DT of their respective cities, the cities have adopted an approach of managing and developing the data environment as a whole, where DTs make up one part of the whole. They envision a DT as a visualisation tool for information in their data ecosystem that can be used as the basis for interactive planning and simulation modelling.

Figure 11: A screenshot from a video about the Den Bosch digital twin (source: https://www.spotinfo.nl/wp/_argaleo/)

The different DTs are currently in an experimentation and pilot phase, used by different instances within the city organisations for visualisation to help planning and decision making. They are meant to visualise recent or real-time information, allow the investigation of past trends and results of actions, test and predict the impacts of planned actions, and to help with public engagement. Examples of realised pilots within the cities so far include a DT related to bicycle traffic, a DT for crowd management, and a DT for tracking and displaying water and sewage problems.

'Je ziet bij ons in het coalitie-akkoord wordt de digital twin genoemd, dat we die ontwikkelen voor het maken van beleidskeuzes. Dus dat is wel het toekomstbeeld waar wij naartoe werken.'
Margriet Heessels, Breda

(You can see in our coalition agreement the digital twin is mentioned, we will develop it to make policy choices. That is the future vision towards which we work.)

The DTs include a base layer of information with the necessary topography and 3D information of the built environments. On top of this base layer, different simulations and information layers can be added per individual use case.

Planned functionalities include real-time information feeds from sensors and real-time analysis, for example in the case of crowd management where a DT can be used to visualise and monitor the volume of pedestrian traffic within the city centres, and provide automatic alerts if some safety limits are exceeded.

The DTs are planned to be used by multiple instances within the cities, with the ambition to make them a part of the toolbox for decision making by professionals within the city organisations, but also potentially for political decision making.

Process and problems faced

The DT and data management projects in both cities started around 2020-2021. In Breda, the trigger was a strategic decision in the 'bestuursakkoord' from 2018 by the political leadership of the city to start working on digital transformation, which was translated into an actionable master plan for digitalisation in 2020 where digital twins were explicitly included *(https://smartcitybreda.com/wp-content/uploads/2020/10/0178_20-BREDATA_master_V8_internet.pdf)*. This ensured stable financing and the organisation to start exploring and developing the use of digital twins and related data technologies.

In Den Bosch, the trigger was similarly political-strategic, with an official ambition to become a 'data city' declared by the mayor in 2018, and driven by a growing 'data cluster' of actors and institutions involved with data innovations. The COVID-19-crisis that started in 2021 served as a contributing factor to accelerate digital innovation in both cities, including the development and use of DTs. In the Den Bosch 'coalitieakkoord' from 2022 there is also an ambition to innovate with data under the heading '2. Innovatie om mensen te helpen.' The digital twin (3D City Model) is now a part of this.
(Source: https://bestuursakkoord.s-hertogenbosch.nl/bestuursakkoord-2022/slagkracht-op-hoofdopgaven?overlay=1.4-Datastad)

The DTs and their associated data management framework are being developed internally with the cities leading their own projects, but also including commercial and academic partners in one of the pilots.

The cities report that there are both knowledge-based and organisational barriers to DT development and use. While many potential users are enthusiastic about the technology and its opportunities, they often lack a clear understanding of what it could do for them, which hinders effective development and organisational embedding. In terms of organisational barriers, the existing processes for project management, their structuring and their financing do not allow much flexibility to accommodate experimenting with and using DTs in projects. Furthermore, the restructuring of data management and organisational changes needed to make DTs useful is a new problem and remains an ongoing challenge for municipalities.

Results

Both cities report that the pilots and experimentation have been received with enthusiasm, and the political ('bestuurlijk') support within the municipalities for continuing work on DTs and related developments is strong, but they are not yet at the stage to evaluate concrete outcomes of actual implementations.

The cities have been expanding and tightening their network of partnerships. For example, in Breda, the first interns from academic institutions have already done work on their digitalisation projects. Both cities have also been involved in pilots of DTs and related technologies by external institutions, for instance Crowd Safety Manager by Argaleo with a pilot implementation in Den Haag.

Future vision

Both cities share a vision that a broad data ecosystem is required, as part of a broader digitalization strategy, on top of which different DTs can be formed to visualise the data. So, the cities work on multiple DTs in parallel. The DTs are seen as part of a toolbox for decision making by professionals and for political decision making. A future ambition is the integration of multiple domains into a 'complete' DT of a city if necessary.

The way these interviewees envision the system around the use of DTs seems to imply a layered and logical structure: A first layer for data input (either secondary data from various sources or primary data from sensors or any other measurement instrument managed by the municipality); A second layer for checking, cleaning and standardising data; A third layer for storage and making data accessible; A fourth layer for visualisation of data and finally a fifth layer for modelling and simulation.

This way of structuring data allows a broader digitalisation strategy than just the use of DTs. It supports the use of AI and other technologies and digital innovations in the future.

Municipality Den Haag: ‘Digitale Spiegelstad / Digital Twin’

Based on an interview with Stefan Los

The digital twin and its use

Den Haag has a dedicated programme for the development and implementation of DTs of the city for various use cases. There is currently no single integrated DT for the entire city but a number of closely integrated applications with varying degrees of maturity and an explicit vision of increased future integration between these applications.

Figure 12: An image from the website for the digital twin used in Den Haag (source: https://www.nederlandin3d.nl/denhaag/?lang=nl&startingmap=Cesium%20 Map&cameraPosition=4.31071%2c52.08037%2c142.19931&groundPosition=4.31306%2c52.07990%2c1.54862&distance=220.56&pitch=-39.62&heading=108.09&roll=0.23&shadowTime=1625138792338#/)

The applications are at different stages of maturity. An example of DT involvement in Den Haag was in the Crowd Safety Manager by Argaleo demonstrated in Scheveningen, in collaboration with the Province of South Holland, Delft University of Technology and the police department. This uses 3D information combined with live data sources from within the area for indicators such as pedestrian density and noise levels. Scheveningen, because of the beach, experiences traffic jams and crowding on sunny days. The DT was developed to monitor and provide information that can be used to intervene. *(https://agendastad.nl/digital-twin-dashboard-geeft-inzicht-in-maatschappelijke-opgaven-den-haag/).*

There are multiple use cases in active development focusing on the physical domain. Three of those are highlighted here. The first is the combination of BIM data into a central DT of 3D information, to store data, track changes, use as a design tool, and help coordinate maintenance of assets. The second is a DT implementation for the management of the energy transition, including simulation of sunlight and other conditions relevant for solar panels and renewable energy, a central display of information for policymakers such as the energy labels of buildings in different areas, and to assist individual residents and other actors within the city in projects related to energy use and production. The third case is dynamic accessibility, where a DT implementation is meant to help combine data about events, maintenance, and projects within the city and over time, to coordinate and minimise unexpected hindrances.

Envisioned future applications include the extension of DT technology into the social and political domains. Increasing the residential density of Den Haag is a challenge, and DTs can help to increase citizen involvement and engagement by displaying alternative solutions to housing more residents. On a technical level, the vision is to increase data integration and quality for a DT that is the 'single point of truth.' That means that the information in the DT does not have to be checked before maintenance or building operations can start.

Process and problems faced

The DT programme started in 2022 was triggered by a statement in the 'coalitieakkoord' that a 3D display of the city needs to be delivered. This statement was then operationalised by establishing the digital twin programme. Conceptual plans and envisioning started much earlier in Den Haag but did not lead to a broad scope programme before 2022.

The DTs are being developed internally within the scope of the dedicated programme, which is a joint initiative between the departments for city design, city maintenance, and information and automatization in Den Haag. The effort involves a dedicated programme team and agile development teams responsible for the development of DTs and related tools, and the maintenance of connections between different domains and departments.

The main barriers to DT development and use within the programme currently reported are organisational and political. Despite there being a dedicated programme for DT development, the relevant efforts are scattered. For example, one relevant service in Den Haag responsible for receiving and collecting geographic data, the Datalab, is positioned in an entirely different department than the DT programme, and has its own goals, mandate and funding unrelated to DT development. There is also no dedicated funding and organisation in place for the implementation of DTs across the city and embedding them into the existing organisation - only their development is funded. A steering group with MT-members (of the municipal organisation) has been formed to safeguard commitment for digitization efforts in general and the development and use of DTs in particular. This committee, however, is still searching for the best way to integrate and implement all efforts. Currently the existence of the DT programme is justified under a 'coalitieakkoord' statement that the department is responsible for delivering a 3D display of the city, but without accounting for the explicit use cases and the integration efforts required to make use of this. This means there is limited political embedding and this is limiting the goals of the programme from being realised because of organisational inflexibility and lack of integral funding.

It is a challenge to create a digital twin that is not just a demo or pilot but that is an integral part of the operation in a municipality. Even a relatively simple type of DT, a 3D-model of the municipality with all the buildings, requires a coordination effort to maintain data accuracy. If assets below the surface are added, like sewage systems, or electricity and telecommunication infrastructure, then the coordination effort increases further.

'Volgens mij is er geen stad in Nederland die het zo voor elkaar heeft dat de ontwerp data netjes naar beheer gaat en terug' (zodat je data een 'single-point-of-truth' vormt voor alle onderhoud, verbouwingen en bouwprojecten in de openbare ruimte).' Stefan Los, Den Haag

(There is no city in the Netherlands that manages to have all design data sent back and forth to the management & maintenance department of the municipality (in order to create a single point of truth for all maintenance, rebuilding and building projects in the public space).)

There are several reasons why the data in the digital twin is not yet 'the single point of truth'. Firstly, all data need to be assessed in reality and then fed into the DT. This is done per category. For asset management, Den Haag starts with the 'kunstwerken' (bridges and so on) then enters the sewage systems, after which the public lighting system will enter. Secondly, all building and maintenance projects in the system may lead to changes that need to be carefully fed into the system. Some of the projects are completed by partners, like KPN (a telecoms provider building and maintaining communication infrastructure) and Dunea (a water utility provider) in Den Haag, and their work also needs to enter the DT. In practice building projects deviate sometimes from the plan. If the data from plans are then fed into the system, the system will not provide the correct data. In practice, all data needs to be checked manually in real life, and this will probably continue for the next 10-15 years according to the programme manager until new technologies with drones, sensors, pointclouds and so on replace this effort.

An issue that all municipalities mentioned during the interviews is the required standardisation of data. If multiple DTs are developed in parallel and these DTs are integrated later on, then the standardisation of the data and the process of building, testing and using DTs has to be aligned and standardised.

Results

The crowd management pilot in Scheveningen will be extended. This DT remains separate from the DT that makes a full 3D-version of the city. The other DTs are in the pilot stage or are even less mature.

Future vision

The programme manager focuses on lower level DTs first before moving on to higher-level DTs. This means that the development of higher level DTs is postponed. The programme manager envisions how the DT for asset management could form an integral part of the asset-life cycle, including permits, design, maintenance, rebuilding, and so on.

Extra Interviews and Workshop to put the Results into Perspective

Province North Holland: Digital Twin Noordzeekanaalgebied

Based on an interview with Noor Bouwens and Arny Plomp

The Province of North Holland, as part of a digitalising strategy, has developed several digital tools, including digital twins (DTs). A pilot was started to create a digital twin of the area around the 'Noordzeekanaalgebied' (NZKG). The goal of the DT is to explore how to optimally use the limited space in this crowded area. There is a need for good oversight of the practical implications of proposed policies or actions across multiple domains that compete for the same space.

The current DT in development is a 3D visualisation (level 1 DT). The primary goal is to visualise alternative uses of the same area. Additional applications and functionalities depend on question-formulation within the province, but the vision is that the DT will become a basic dataset and tool for evaluating long-term effects of actions and policies adopted by the province. An example of a policy that can be evaluated using a digital twin of the area is the decision to have a new housing estate and its effect on traffic streams or flood risk in that area. Another example is the possibility to install wind turbines and the resulting noise nuisance. The DT is seen as a tool to eventually visualise scenarios and assess the consequences of each scenario in terms of a variety of variables.

The province aims to create a data foundation that can be used by multiple tools and for multiple types of analysis. On top of this foundation, the first application can be built and then new ones can be added later. This means in the short term a 3D visualisation is built (a level 1 DT) that can be used for long term policy formulation and testing. Later on, after adding data, other types of use can be gradually complemented. Around the data and tools a kind of portal is created that allows contributions from and applications for various stakeholders. Collaboration and standardisation is essential to make digital twins use promising for policy purposes

This modular approach and the initial experimental demonstrations are important because stakeholders, for example policy makers within the organisation of the province, and partners active in the province, need help with imagining the use of DTs and the consequences of this use for their daily operations.

Digital Twins in Homes

Based on an interview with Martin Pot

Digital technologies and recent digitalisation related to home and building development have been primarily focused on the production and construction of housing, where the focus of the process is on design and construction. The basis for this are tools like GIS, BIM, and other construction and building management systems. This has impacted the agenda driving digitalisation in urban environments, with the focus typically being on the objectives of municipalities, planners, commissioners, and builders. However, digital technologies have increasingly spread into the lives and homes of individuals, which has led to concerns regarding privacy and security, but also presents an opportunity. New data-driven technologies could allow closer involvement of the individual in the process of urban development from the start, making them central stakeholders in the design and building process rather than mere passive end-users, and giving individuals greater agency over the long-term use and development of their homes and environments.

In the context of homes, digital twins and the family of related technologies can serve two purposes. The first is the integration of the future inhabitants into the process of planning, development, and construction instead of them simply being the end-users. This is achieved through increasing the digital awareness of inhabitants and greater accessibility of data technologies for interaction and visualisation. Secondly, the new technologies can become an integral part of the long-term future of homes, providing the flexibility through data and interaction to respond to changing future needs (and possibilities) because of societal changes and because of the changing needs of individuals throughout their lives. These technologies can affect and help with addressing the process of building homes for the next 150 years, given that we do not know what society will be like in 25 years.

Insights from the STT Workshop

(2023-03-29)

On the 29th of March 2023, Capgemini hosted a meeting for STT-members. As part of that meeting initial results of the digital twin project were shared, after which Capgemini moderated a workshop to discuss the problems and to provide possible directions regarding the development and application of digital twins in municipalities. We would like to share a few insights from the presentations by STT-members and their questions after our presentation.

Several groups stressed the importance of involving different stakeholder groups. The implementation of digital twins in the day-to-day operation of municipalities may be a ‘dream’. The question was raised: Whose dream will it be? Is the digital twin just another process innovation that speeds up, facilitates and hence reduces the costs of the internal operation of municipal organisations? Or is the digital twin a tool that helps to arrange issues that are important for citizens? Citizens, for example, *'Digital Twin is een tool en geen doel'*

(Digital twin is a tool, not a target)

would like municipal organisations to dig up their street just once instead of multiple times. That requires a well-organised building and maintenance plan, which can be formed and tested using a digital twin (as the municipality of Den Haag is now demonstrating). Similarly, citizens would value a quick response by municipal authorities to prevent major traffic jams and severe local air pollution, both of which are possible using digital twins. Finally, digital twins could be used to involve citizens and have them participate in city developments.

During the meeting, several STT members stressed the stepwise and iterative nature of developing and applying a digital twin. Implementing digital twins for municipal operations is a kind of moving target starting with a simple problem and then after evaluation and learning, it may be used to solve other problems and enable other applications.

Cross-case Analysis

In the cross-case analyses we combine the findings from the interviews, in particular the interviews about the use of DTs in the municipal environment. In the first subsection, we will report the type of DT applications used in municipalities. For each application we will discuss the type of DTs and their result, in terms of the maturity and scale of use of the DT. In the second subsection, we will report on the process of development and implementation of the DTs. In this subsection we will also describe how each of the municipalities is adept in specific aspects of the process. This subsection thereby not only provides a list of issues to deal with when developing and implementing DTs, but may also inspire other municipalities. In the last subsection, we describe how the future visions of the municipalities differ and how these visions can be contrasted in a general framework. This may, again, inspire other municipalities to formulate their own vision.

DT Use and Results

During the interviews several applications of DTs came to the fore. An overview of these applications is provided in Table 5.

Table 5: Different applications of DTs mentioned during the interviews

	Municipality	Application	Level of DT	Result
1	Amsterdam	The DT includes detailed representations of buildings, roads, canals, vegetation, and underground plumbing. These are complemented by airborne image layers, and zoning and planning maps over time. There is rudimentary simulation of sunlight and shadow with pre-set weather conditions.	Level 2: D-representation with a few layers with information and limited simulations	Implemented and widely available on-line on personal computers and tablets for civil servants, architects, engineers and the wider public
2	Amsterdam Breda / Den Bosch	Use of the DT by planners and policymakers. DT with detailed representations of buildings, roads, canals, vegetation, and underground infrastructures (cables sewage systems, and so on)	Level 2: D-representation with a few layers with information and limited simulations	Only an idea of future use. Planners and policymakers are interested but this is not yet realised.
3	Den Haag	Envisioned future applications include the extension of DT technology into the social and political domains. These are for the ongoing challenge of increasing the residential density of Den Haag, and for increasing citizen involvement and engagement through the use of DTs as a display technology.	Level 1	Plan, idea that is yet to be materialised

	Municipality	Application	Level of DT	Result
4	Den Haag	A DT implementation for the management of energy transition, including simulation of sunlight and other conditions relevant for solar panels and renewable energy, a central display of information for policymakers such as the energy labels of buildings in different areas, and to assist individual residents and other actors within the city in projects related to energy use and production.	Level 1	Pilot
5	Den Haag	The combination of BIM data into a central DT of 3D information, to store data, track changes, use as a design tool, and help coordinate maintenance of assets. The plan is that the DT becomes the single-point-of-truth. Currently this is not the case so all data need to be checked manually in real life, this will continue probably for the next 10-15 years according to the programme manager.	Level 1 DT to give a 3D representation of different layers	Pilot stage
6	Den Haag	The third case is dynamic accessibility, where a DT implementation combines data about events, maintenance, and projects within the city, over time, to coordinate between these and to minimise expected hindrance for traffic. This case provides an overview in time, an agenda, and requires standardised data from the different sources.	Level 1-2	Pilot
7	Amsterdam	Use of the same DT to involve the general public to inform about and involve them with changes in the city.	Level 1-2	Only an idea of future use. The idea is that the general public can be involved better.
8	Breda and Den Bosch	Crowd and traffic control. A pilot has been completed for bicycle traffic. Planned functionalities include real-time information feeds from sensors and real-time analysis, for example in the case of crowd control where a DT can be used to visualise and monitor the volume of pedestrian traffic within the city centres, and provide automatic alerts if some safety limits are exceeded.	Level 3 is planned	Pilot experiment
10	Breda and Den Bosch	Health and liveability	Level 2 and higher	Pilot experiment
11	Breda and Den Bosch	Water and sewer system management. A pilot has been realised for tracking and displaying water and sewage problems.	Level 1 and 2	Pilot experiment

Process and Problems

During the interviews it became clear that developing and implementing DTs within a municipality is a highly complex process facing many barriers. The decision to develop a DT requires a vision of what a DT is and how it can be best applied. In practice such a vision is often formed as part of a digitalisation agenda in an iterative process during development and implementation. The development process requires a type of funding that is not readily available in municipalities, the domains have earmarked budgets and it is difficult to fund a tool that may provide benefits for multiple domains. The implementation process requires a change in existing procedures and processes and that disrupts and hence evokes resistance. Furthermore implementation involves multiple actors outside the municipality and that requires coordination, network formation and dealing with resistance at times. In short: it is a challenge. To encourage and help municipalities, we will first describe how each of the municipalities was particularly good in specific parts of the process of developing and implementing DTs. We will then proceed with a generic list of issues.

Each municipality is proficient in specific aspects.

Each city has a particular way to further the development and implementation of digital twins. We have several observations from the interviews that highlight important aspects. Each of the municipalities turned out to be good in some aspects, specified in the following subsections with tables.

Amsterdam

Table 6: Aspects regarding DT development and implementation covered relatively well in Amsterdam

Topic	Observation	Benefit
Focused and rapid implementation	The DT project is aimed at very focused applications with a clearly known need.	This has helped going from idea to implementation very quickly even with limited resources, and practical results have already been achieved with a real implementation.
Accessibility	The DT is designed to be as open and accessible as possible at all levels in terms of ability to use and download data, ability to integrate more data, and open access for the public through a web implementation.	This helps with making the DT a relevant and accepted tool and information source for a broad range of actors.
Established users	There is a clear established user base for the DT.	This helps the continuing development through feedback from users with tangible use cases.

Breda and Den Bosch

Table 7: Aspects regarding DT development and implementation covered relatively well in Breda/Den Bosch

Topic	Observation	Benefit
Political embedding	There is deep political embedding (coalitie-akkoord with approval from 'gemeenteraad' that is an integral part of long-term plans) of DTs in terms of political support and published policy for digital transformation.	This minimises organisational barriers to DT development and implementation
Dedicated funding	There is a stable status of dedicated (long-term) funding for the projects for exploration, development, and implementation.	This is a necessity in an organisation where existing departments lack the budget in the domain of digital transformation and implementing radically new tools and processes across departments.
External network	There is a broad external network of local actors from various domains (policy, commercial, education and academic).	This supports the societal and political relevance of DTs, and also provides access to a greater variety of skills and use cases. This helps to share experiences and learning effects.

Den Haag

Table 8: Aspects regarding DT development and implementation covered relatively well in Den Haag

Topic	Observation	Benefit
Understanding applications	A deep understanding within the programme of what questions DTs can be used to help address, and the tangible benefits this could deliver to the city and different stakeholders within it.	This helps maintain political support and helps the delivery of demonstrable results in the short-term.
Logical ordering of applications	There is a clear view of the ordering of different applications in terms of what can be practically achieved in the short-term, but also the long-term potential, and how future applications build on past applications. For example, the 3D-model for asset management will first cover bridges and so on ('kunstwerken'), then the sewage system will be covered and finally public lighting.	This helps prioritise resources towards the most relevant current applications with the highest chance of success, while providing a clear path towards the development of DTs for future applications.

A generic list of aspects

In the previous section, we summarised how each of the municipalities was doing relatively well in one or more relevant aspects regarding the development and implementation of digital twins. In this section, we combine the relevant aspects and turn them into an initial list of important aspects that municipalities may consider during the development and implementation of digital twins. For each of the aspects we have formulated three levels: a ‘base level’, an ‘intermediate level’ and an ‘advanced level’. This section results in an audit that municipalities can use to assess what their current situation is.

Table 9: Combined aspects regarding DT development and implementation that can be used as audit list

Aspects	Levels of the aspects		
	Base level	**Intermediate level**	**Advanced level**
1 Political embedding	**General agenda** General Digital agenda and some projects are formulated to implement parts of the agenda.	**Programme of projects** Responsible ‘wethouder’, overseeing a portfolio (or programme) of complementary projects, pilots and initial applications.	**Coalitie-akkoord** General Digital agenda is part of the ‘coalitieakkoord’ and projects formulated to implement parts of the agenda are politically approved.
2 Organisational embedding	**DT in Domain** Work on DTs is seen by separate domains (parts of the municipal organisation) as a way to experiment and pilot. Commitment by manager of a domain.	**DT for multiple domains** DTs are developed and managed across multiple domains for the entire municipal organisation with top management support.	**DT for domains and policy** DTs are an integral part of the day-to-day operation within and across domains and serve as planning and participation tools for the political organisation. The required changes in work processes in domains, to be able to use DTs, are implemented.
3 Type of funding	**External short-term** External project funding, for example from a ministry, from VNG or any other external source.	**Internal short-term** External and internal project funding from within the municipality.	**Long-term** Long-term (permanent) funding (like for domains of the municipal organisation).

Aspects	Levels of the aspects		
	Base level	Intermediate level	Advanced level
4 **Internal network**	**One domain** Development and use of separate DTs within one domain of the municipal organisation.	**Multiple domains** Integral development and use of DTs across domains of the municipal organisation.	**Domains and policy** Integral development and use of DTs across domains of the municipal organisation and across the political organisation.
5 **External network**	**Municipal partners** Network consists of some other municipalities.	**Diverse partners** Network consists of diverse partners outside the municipal organisation, such as: companies, other municipalities and knowledge and research institutions.	**Diverse partners across NL** Network in which all municipal organisations join forces with companies, other municipalities, knowledge and research institutions and various customer groups.
6 **Understanding applications**	**Demo** Initial applications are envisioned to start a demo or a pilot.	**Use-cases** In each application, the customers and their needs are known, the added value of the DT for the customers is made explicit.	**Business-cases** In each application, next to added value for customers, the required data are specified, and (the change in) work processes to apply the DT, the costs and the benefits of using the DT are fully specified.
7 **Ordering of applications**	**Some potential applications** There is an initial list of alternative potential applications of a DT but no order yet.	**Full list and initial focus** There is a complete list of alternative DT-applications, and development and piloting of a DT for an application starts with a specific request of a customer, or with external funding creating an opportunity.	**Full list and explicit order** There is a complete list of alternative DT-applications, and an explicit analysis of the logical order in which DTs can be developed and used for applications and customer groups.

Aspects	Levels of the aspects		
	Base level	Intermediate level	Advanced level
8 **Implementation (scale and maturity)**	**Explore** There are one or more projects to explore the use of DTs in an application.	**Pilots and use-cases** One or more applications are developed into a pilot for a use-case.	**Applications** One or more applications are approved after piloting and are now available for actual use.
9 **Accessibility for different customer groups**	**Developers** The DT is only available for people developing and exploring DTs.	**Users in domain(s)** The DT is available for internal use in a domain.	**Multiple stakeholders** The DT is available to multiple customer groups within and outside the municipal organisation.
10 **Basic architecture and standardisation**	**Context DT standards** For a specific DT as applied in one municipality, data requirements and usage processes are explicitly standardised.	**General DT standards** For different types of DT, a common data and usage process standardisation is adopted to allow the combination of multiple (layers in) DTs, meeting legal requirements (e.g., AVG) and data-protection requirements and with explicit division of who can use particular DTs or change particular data and tools.	**Digitalisation standards** For different tools (DTs, dashboards, AI-applications, websites and so on) there is a common data platform and usage process standardisation to allow the combination of multiple data and multiple tools, while meeting legal requirements (AVG) and data-protection requirements and with explicit division of who can use or change particular data and tools. Explicit protocol to check and keep data up-to-date so that it becomes a single point-of truth.

The audit list specifies 10 aspects, which emerged during the interviews or from the analysis thereof. It is interesting to notice that these aspects have to do with the aspects surrounding the DT rather than the DT itself. The main issues are not related to technological limitations or issues that require basic research but rather organisational aspects that have to do with implementation and applied knowledge.

This list is not exhaustive but we are confident that each of the aspects needs to be considered by municipalities aiming to implement DTs. These municipalities can consider the levels that we formulated to assess where they stand. The three levels simplified and for some aspects it is easy to formulate more levels. The aspect ‘Basic architecture and standardisation’ for example, could have a fourth level in which standards are set across municipalities.

Each of the municipalities perform well in one or more relevant aspects, but none of the municipalities is covering all aspects on level 3, as can be expected for a relatively recent phenomenon still in development. If political embedding, organisational embedding and type of funding are not moved to level 3, it is highly likely that the efforts to develop and use DTs will come to an end. Many potentially useful technological innovations go through prolonged periods of piloting and small-scale applications, after which they die out and are not implemented widely.

Timing is crucial, and to safeguard development and application, funding needs to become more permanent. But that can only be arranged when the first applications are implemented and show their value for an engaged customer group and thereby stimulate more wide-scale implementation and use among other customer groups. So, understanding applications, and a vision of the logical order thereof, are crucial to prevent a sudden death of potentially useful tools like DTs. This is true within municipalities but this is also visible in general on a higher level, when we look at the pattern of development and diffusion of DTs (see Part I or the appendix describing the Technology Monitor).

The basic architecture and standardisation aspects represent a necessary condition for more wide-scale use beyond local demo’s and pilots. If the standardisation is not properly arranged, then later on during development and use, this will create severe accidents (e.g. data leakage and misuse) or limit progress. In short, all of the aspects being incomplete or on a low level, can block progress. Conversely, all of the aspects need to be taken into account for more permanent and wide-scale use.

Future Vision

It is interesting to see how the interviews revealed widely different visions about the future. Amsterdam focuses on a specific application of a DT, the 3D-model of the city, and has made that widely available inside and outside of the municipal organisation. Their vision is to develop this model further to turn it into a country-wide 3D-representation. In Amsterdam and Den Haag, different DTs are developed in parallel. In Den Haag, the crowd-management DT in Scheveningen is separate from the asset management DT in Den Haag. In Den Haag a logical order of DT-applications is in progress. Both Den Haag and Amsterdam do stress that technically level 1-2 DTs should be implemented and used first before higher level DTs are to be developed. In contrast, Breda and Den Bosch explicitly consider DTs fed with real-time information (level 3 DT). All municipalities are aware that standardisation issues are crucial.

In the next chapter we will more generally describe alternative future development directions regarding the development and use of DTs.

Conclusions

The Technology Monitor in Part I showed that digital twins (DTs) are in the adaptation phase, meaning that they are not yet applied on a large scale. We also concluded in Part I that social and organisational aspects rather than technological aspects currently limit wide-scale use of DTs. In Part II, we zoomed in on municipal organisations. Within the relevant (network of) actor(s), which is only one of the 14 factors in the framework of the 'Technology Monitor,' we see many relevant subfactors when we focus on municipalities.

Part II illustrates that development and implementation of technological innovations, like the DT, is an evolutionary process. Municipalities had different reasons and triggers to start working on DTs, some of which accidentally shaped the evolutionary path (such as the COVID-19 pandemic). For example in Amsterdam, the Omgevingswet was initially the reason to start working on a DT, but it was not approved in the expected timeframe and hence other applications were developed.

Each of the municipalities form separate networks of partners, have different paths of development, and have different visions about the use of DTs in the future. We conclude that both within municipalities fragmentation is visible, and across municipalities and their distinct networks, fragmentation is visible. This fragmentation and the accompanying lack of standardisation may hamper further development and use, later on. It is about time to limit the fragmentation, join forces, learn from each other, reuse models, establish common standards and architecture and then align future development paths.

Part III

A Look Ahead: Options for the Future

3

Introduction

The Stichting Toekomstbeeld der Techniek (STT) in most studies focuses on societal domains, like education or transport, and describes how these domains change over ten years or more. The uncertainty that comes with the long-term perspective means that STT explores rather than predicts the future. Hence, scenario studies are often used to explore the interaction between multiple technologies and social aspects within one domain. The Technology Monitor is complementary to the domain-specific approach because it focuses on one technology and how it has developed and has been applied in multiple domains in the past.

In Part III, we explore how the Technology Monitor approach can be extended to look ahead. Looking ahead is important because the results of the 'Technology Monitor' can then serve as input for other STT studies and because STT members can then use the results to formulate interventions, strategies or policies to prepare for or influence the future. Just as with the domain-specific approach, the objective of an extended Technology Monitor is exploring the future rather than predicting it. Highly contextual and uncertain information does not offer a robust basis for exact predictions.

We will extend the 'Technology Monitor' approach in three steps. First, we will adopt an actor-focused perspective by taking the perspective of a municipality and then describe in which directions the municipality can extend its activities with DTs. We translate these insights into an actor-focused framework of analysis. The framework can be used by municipalities to map their current position versus their ambition regarding DTs. Second, we will adopt a technology-focused perspective showing in which directions DTs can be developed and applied in general (across municipalities and industries). These insights are also translated into a framework with dimensions reflecting possible directions of change. Third, we will discuss how these insights can be generalised and used for other technologies.

So, these steps result in complementary frameworks that can be used in tandem. The actor-centred framework can be used to formulate interventions, strategies or policies and thus makes the Technology Monitor results actionable. In contrast, the technology-centred framework can be used to explore how the technology, because of the joint efforts of many actors, can develop further and thus makes the Technology Monitor results valuable input for societal scenarios.

Just as with the domain-specific approach, the objective of an extended Technology Monitor should be exploring the future rather than predicting it.

An Actor-Focused Framework for Digital Twins

Purpose and Directions of Change

The purpose of an actor-focused framework for DTs is to have a tool for individual municipalities to evaluate their positioning and envision possible directions of change. Once the position and possible directions of change are visible, municipalities can anticipate relevant possibilities and risks, and then set ambitions and develop policies.

We identified three dimensions reflecting possible directions of change:

1. The technological level of the DTs: This was formulated in Part I, and in Part II we observed large differences in the current levels of DT being worked with and the goals the cities are working towards. These ranged from storage and display of 3D information to the integration of simulations and sensor data to systems that would automatically manage traffic or asset maintenance, what we would define as DTs from level 1 up to level 4. We can simplify this into a dimension of DT level. For this dimension, the relevant audit list factor is political embedding, as the political process drives the desired technological level.

2. The number of different applications or use cases: In Part I we observed that DTs have applications over a broad range of sectors and use cases, and in Part II we observed this also holds for municipalities and other urban actors. The differences here range from very focused use on cases that require reliable 3D information to public engagement, policy making, and active management in use cases such as design, maintenance, planning, public safety, and energy management. This range of differences observed can be simplified into a dimension of the number of applications. In terms of the audit list, particular impact factors for this dimension are the type of funding, understanding and ordering of applications, and level of implementation.

3. The scale of the collaborative networks: The cities have varying scales of networks related to their work with DTs as observed in Part II, namely how many other cities and urban actors they are networked with and collaborating with in a substantial way. Here we see variation in practice from closely local external networking to networks of multiple cities and ambitions reaching as far as countrywide collaboration. They also exhibit different degrees of internal networking, ranging from collaboration within a single development team to collaboration across the entire municipal

organisation on multiple levels. This is then simplified into a dimension of scale of collaborative networks. Particular audit list factors relevant here are the organisational embedding, status of internal and external networks, accessibility for different customer groups, and basic architecture and standardisation.

It is interesting to see how each direction of change (reflected in dimensions) requires that particular aspects need to be taken into account. A general list of aspects is presented in Table 10 of the previous chapter. Several subsets of aspects are important in each direction of change.

Actor-focused Bounded Dimensions Model

The dimensions reflect possible directions of change that a municipality can decide to pursue. A political decision sets the ambition to change in a particular direction. Some municipalities pursue just one DT application but would like to roll that out in collaboration with many actors (hence they primarily move on dimension 3). Other municipalities pursue multiple applications within their own municipality by collaborating with a few actors (hence they primarily move on dimension 2). Actual change will depend on the interaction between policy interventions, behaviour of other stakeholders and boundary conditions.

The dimensions and bounding factors are visualised below in Figure 13. When the municipality is placed in the focus, we can use the dimensions to describe the current state of DT development and use in a municipality, the ambition in terms of these dimensions, and the current state of political bounding on these dimensions. The current state, ambitions, and bounding can then be related to each other to identify and anticipate possibilities and risks and to help formulate strategies for the future.

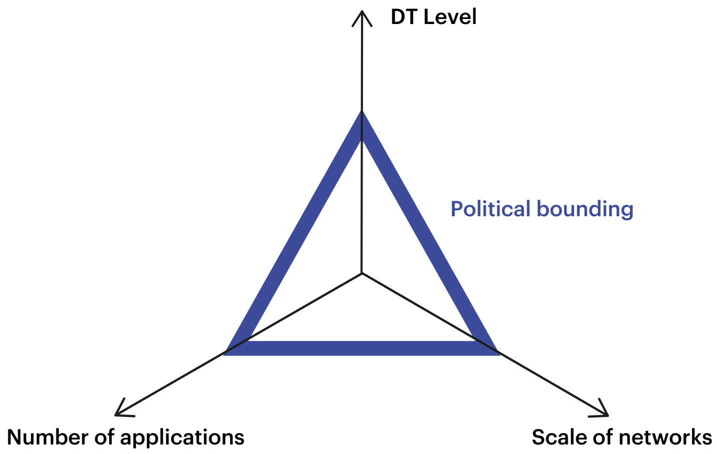


Figure 13: Three-dimensional system combining different paths of DT-development for municipalities

Effects of Political Bounding, Positioning and Ambitions

In practice, the political bounding sets the most explicit limits along the dimensions. We delineate some examples:

1. The DT level may be bounded by ethical choices since municipalities are social environments in which individual rights such as privacy must be protected, and shifting control of important affairs to increasingly digital and automated systems may be undesirable from a value standpoint.
2. The number of applications may be bounded by strategic choices within the DT programmes and the political administration of the municipalities, for instance if there is a mandate for only a small number of specific use cases, or if financing and resources are limited due to lack of political embedding.
3. The scale of networks may be limited by lack of political embedding that hinders the establishment of collaborative relationships between different departments within municipalities themselves, and external actors in the urban environment.

The relationship between positioning and ambitions along these dimensions present their own possibilities and risks. We can define two broadly defined sources of risk: ambition mismatch, and tunnel vision. Ambition mismatch means the future ambition being worked towards vastly exceeds the current positioning that can be practically achieved. This leads to a risk of insufficient focus on the practical short-term in favour of long-term visions, which can paradoxically undermine the long-term ambitions if no short-term results are achieved. Whereas long-term visions are essential in a political context and within socially focused institutions such as municipalities, short-term results in innovation development and implementation are necessary for learning and maintaining relevance and support.

Tunnel vision means there is an excessive focus and one or more dimensions or the political bounding effects are neglected. This can lead to an overcommitment of resources towards advancing along one dimension, but the lack of commitment towards the rest may ultimately undermine the efforts that went into the main focus.

Example Analysis

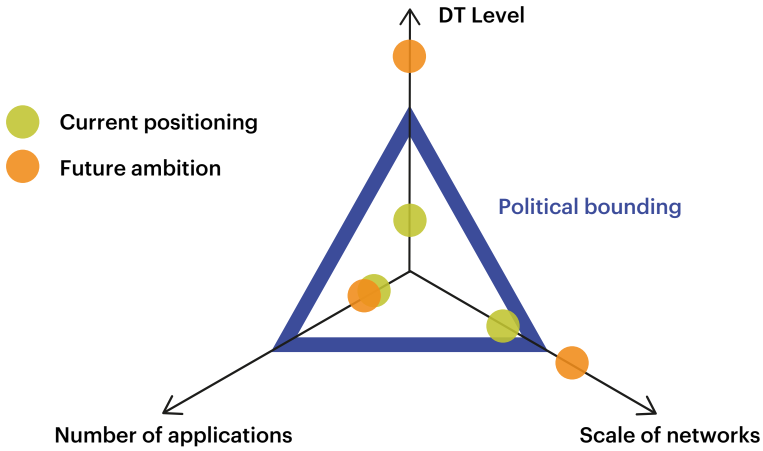


Figure 14: Examples of DT-development positions compared with ambitions

In Figure 14, we have mapped out the positioning and ambitions of a hypothetical municipality and we describe three different situations. For the first situation, have a look at the green/orange dots on the dimension 'Number of applications'. We see a close matching between the current positioning (green dot) and ambition (orange dot) regarding the number of applications that is well within the political bounding. This may suggest tunnel vision where the number of applications is being disregarded - the ambition is well within the current political bounding and has effectively already been achieved, despite the possibility and political feasibility of further development.

For the second situation, have a look at the green/orange dots on the dimension 'DT level'. We see that the ambitions are high and significantly exceed the political bounding. This may be a sign of ambition mismatch, where it may be very difficult to work towards relaxing the political bounds to have a chance of achieving the ambition.

For the third situation, have a look at the green/orange dots on the dimension 'Scale of networks. We see the current positioning close to the political bounds, and an ambition that does not exceed the political bounding significantly. It could be realistic for the actor to obtain political support and relax the bounds to achieve their ambition.

It is interesting to notice that municipalities can differ in terms of their current position (the green dot), their ambition (the orange dot) and their political bounding (the blue lines). They can also differ in terms of in which directions they intend to develop further (as reflected in the dimensions). Over time, political bounding, ambitions and current positions will change.

Additionally, if we instead consider combined actor-focused analysis of multiple municipalities and urban actors, we can now draw conclusions about possible relationships of digital twins with future norms and values. Using the example of ambition mismatch with DT level compared to current political bounding, this may appear to be a hurdle for an individual municipality. However, if a similar case was seen across a broad range of other municipalities, this could suggest that there is an ongoing and upcoming shift in norms and values within the urban environment. This could result in eventual shift in the political bounds. This is then an example of a possible projection path related to future norms and values.

A Technology-focused Framework for Digital Twins

Purpose and Directions of Change

The purpose of a DT-focused framework is to generate and evaluate options for future development of DTs in an urban environment. We achieve this by taking the previous framework and taking the municipality out of the centre and replacing it with digital twin technology. The three dimensions of this DT-focused framework are adapted and explained:

1. **Technological level of DTs in the urban environment:** This was formulated in Part I, and in Part II we observed large differences in the current levels of DT being worked with and the ambitions that urban actors have. To describe DTs in the urban environment, we simplify this into a dimension of observed DT level.

2. **The number of different applications:** In Part I we observed that DTs have applications over a broad range of sectors and use cases, and in Part II we observed this also holds for municipalities and other urban actors. This range can be simplified into a dimension reflecting the number of different applications in the urban environment.

3. **The scale of use:** In Part I, we observed a range of variation in the use of DTs across different sectors. To describe DTs in urban environments, we can simplify this into a dimension of overall scale of use within the urban environment.

DT-focused Bounded Dimensions Model

The dimensions and bounding factors are visualised below in Figure 15. With DT as a technology placed in focus, we can now describe the overall state of DTs in the urban environment. This is closely analogous to the actor-focused case, but now the scale of networks is replaced by scale of use when shifting into a technology-focused view. In this view, the notion of ambition is left out since this is an actor-specific descriptor, and we simply map out the current positioning of DTs within these dimensions. For exploration and projection, we can then consider possible future positions in addition to the current position and see how these are related to the current position and bounds to draw conclusions about future development.

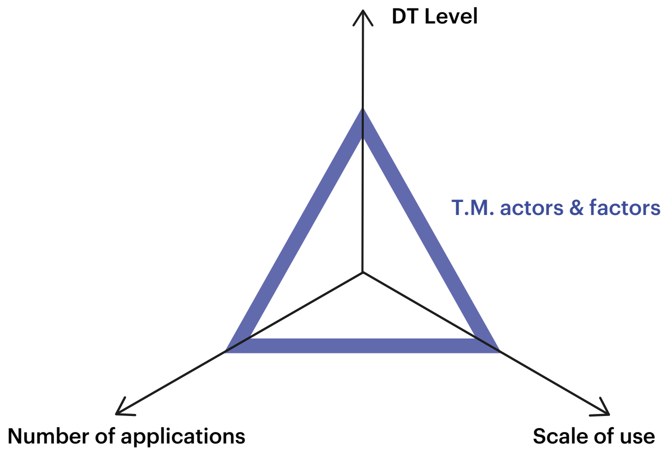


Figure 15: Three-dimensional system combining different paths of development for digital twins

Effects of Actor & Factor Bounding, Positioning and Future Possibilities

When looking at the number of applications and the scale of use, the analysis of bounding effects is equivalent to the application of the Technology Monitor traffic light model while considering technology spread. Bounding effects on the DT level on the other hand capture actor and factor impacts on the technology development, but now on a level basis where each level is considered an individual technology. Each of the individual primary and influencing factors in the traffic light model represent their own bounding effect on the three dimensions.

For exploration purposes, a key metric to observe are the differences in possible future positions compared to the current position, relative to the barriers as formulated in Technology Monitor. This can allow the likelihood of certain scenarios and their implications to be evaluated. In general, the positioning can be either at the barrier, in which case no development along a dimension is expected unless a change in the urban environment removes or relaxes the barrier, or below a barrier, in which case we can expect development in the near-future until the barrier is reached.

Example Analysis

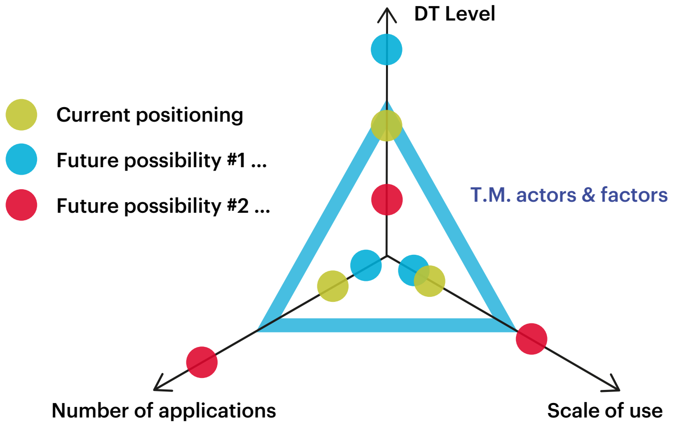


Figure 16: Examples of DT-development positions compared with possible future positions

In Figure 16 above, a roughly estimated current positioning of DTs in the urban environment and two hypothetical future possibilities are mapped out. By definition, the current positioning falls within the current bounding factors, and is positioned either at the bounds or below them in the respective dimensions. Through Part I and Part II we observed that the level of DTs used in general is primarily bounded socially and politically, which means that the current implementation is likely to be technologically to the highest allowed level within the bounds. As such, the current level positioning is at the bound. Furthermore, it was observed that the number of different applications and the overall scale of use are actively growing, and as such we position these below the current bounds.

Future possibility #1 is characterised by an anticipated higher technological level, but a smaller number of applications and lower scale of use. This could for instance reflect a situation in which legal regulation limits the applicability and scale of DTs in a large number of use cases, and instead they become a highly developed niche tool in a specific allowed domain, for instance in infrastructure maintenance, reflected in the higher future level.

Future possibility #2 is characterised by a lower level but a number of applications and scale of use that are beyond the current allowed bounds. This could reflect a case where other tools or technologies overtake DTs technologically such as detailed physical simulations, but simple kinds of DTs spread and become widely used in the urban environment in a number of applications, for instances as simple persistent 3D data repositories for physical objects which are then used in a broad range of use cases to facilitate maintenance, planning, decision making, and public communication, and possibly used as the basis for more sophisticated applications.

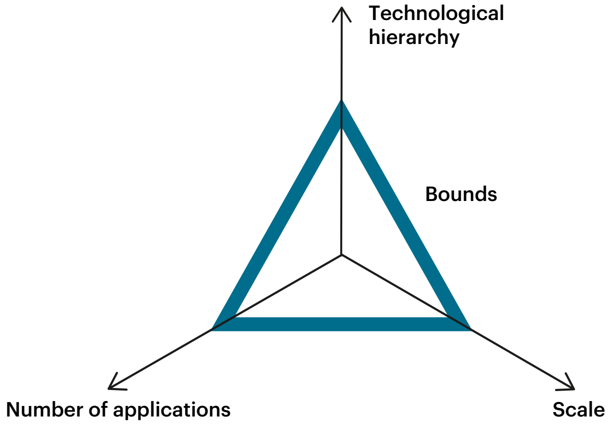
A General Technology-focused Framework

Expansion from DT-focused Framework

Having formulated a technology-focused framework for positioning and exploring DTs in the urban environment, an extension into general use is trivial, so long as some limitations and assumptions are taken into account. The form of the dimensions for a general case have to be adapted somewhat. Regarding the specific dimension 'DT level' (the vertical dimension), this dimension would now reflect some hierarchical classification within a connected family of technologies.

There is also some applicability for analysis of a single well-defined technology, but for this the level dimension should be removed to leave us with two dimensions with bounds based on the Technology Monitor actors and factors.

The specific priority and presence of different barriers would have to be adjusted based on the context of application, for instance if evaluating the maritime environment instead of the urban environment, or a non-physical environment such as a specific market sector. For cases where some kind of hierarchical classification within the discipline or family of technologies is not evident, the framework may be inappropriate. Despite this, the framework presents many useful possibilities for formal long-term exploration within cases that satisfy the necessary assumptions, as now instead of a static unit of analysis as in the traditional Technology Monitor, the framework can be applied to a family of technologies connected to each other over time to generate a specific Bounded Dimensions Model that forms the basis for exploring current positioning, bounds, and future possibilities.



Legend
Technological hierarchy:
specific to tech. family or discipline, such as Level for DTs
Scale:
specific to unit of analysis, such as scale of network for actor-focus and scale of use for technology-focus
Number of applications:
specific to domain of analysis and specific use cases within it, such as use cases within an urban environment
Bounds:
specific to unit of analysis and domain, such as political bounds for municipalities in focus, or T.M. traffic lights for technology in focus

Figure 17: Examples of DT-development positions compared with possible future positions

Connection with the Technology Monitor Pattern

Finally, the general framework for the Bounded Dimensions Models can be connected to the pattern of development and diffusion in the Technology Monitor. This results in a description that can now account for disciplines or families of connected technologies over time, instead of just the overall phases of a single technology. These connections can be made for each dimension and the bounds of the general framework as follows:

1. **Position in technological hierarchy:** This dimension relates to the fact that as one technology evolves through its pattern, this may lead to the beginning of an entirely new pattern. A digital twin of a given level may lead to the development and diffusion of a DT on a new level, considered a new technology.

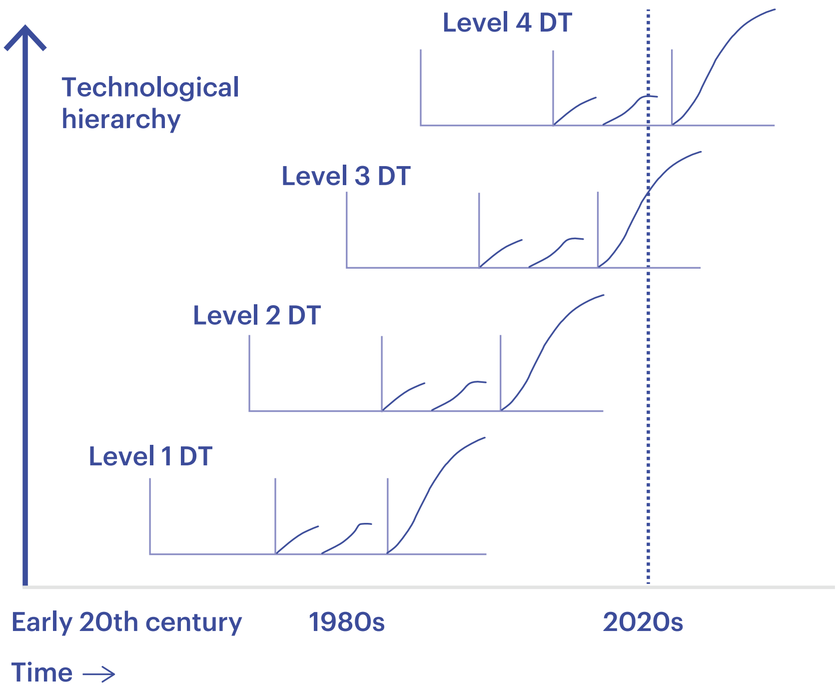


Figure 18: The dimension 'technological hierarchy' distinguishes between related yet different technologies, for each of which a pattern can be established.

2. **Number of applications:** In the Technology Monitor, the pattern is a single picture that describes the development and diffusion of a technology. The number of applications can be used to capture the development, as we can assume that to become viable for additional applications, the technology must develop further. In Figure 19 this is reflected in the evolution of application 1 into application 2.

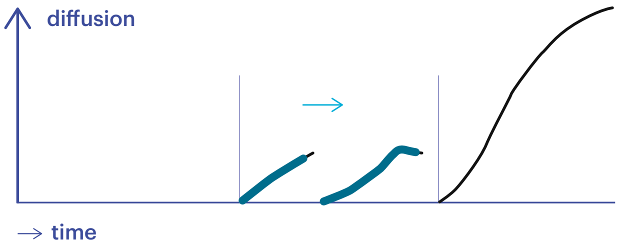


Figure 19: The dimension 'number of applications' refers to a shift within a pattern from one application of a technology to another application.

3. **Scale:** This can be related to the notion of spread in the standard pattern. As the technology spreads, the scale of use in general and per application will increase.

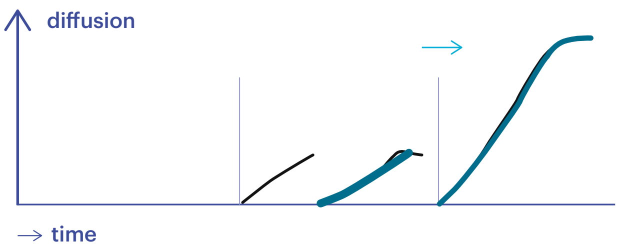


Figure 20: The dimension 'scale' refers to a shift within a pattern from niche to large-scale applications.

4. **Bounds:** When considering bounds particularly for the scale dimension, this can essentially be described by the standard traffic lights of actors and factors from the Technology Monitor, describing the barriers and supporting factors for the start of large-scale diffusion. In terms of the number of applications dimension, this can be similarly related to the traffic lights, but now with actors and factors in consideration that specifically impact development into new applications. Lastly in terms of the technological hierarchy dimension, we must consider a highly modified set of actors and factors, as this dimension reflects a shift into an entirely new technology with its own pattern.

Particularly in a societal context, technologies and their development and spread are rarely independent or isolated phenomena. This is why a multi-dimensional description that can be related to multiple connected technologies and their surrounding social and market context is a valuable extension to the standard Technology Monitor.

Recommendations

4

In this final chapter we focus on recommendations. Different sets of recommendations can be formulated on the basis of the parts in this report, and each of these sets of recommendations addresses somewhat different subgroups. The first set of recommendations is based on Part I (Digital Twins in General) and can inspire policy-makers and managers in organisations (either supplying or using digital twins). The second set of recommendations is based on Part II (Digital Twins in an Urban Environment) and can inspire professionals in municipalities. The third set of recommendations is based on Part III (A Look Ahead: Options for the Future) and can inspire professionals in municipalities.

Recommendations from Part I - Digital Twins in General

The Technology Monitor for Digital Twins (Part I) revealed that high-level digital twins are currently only used in small-scale niche applications. Selected companies use such DTs to control industrial processes, for example. That seems in sharp contrast with the fact that DTs have been mentioned, developed, and applied in many places and for decades. Yet most of these DTs refer to lower-level DTs e.g., 3D visualisations with limited simulations but without real-time data-input from a base system, or feedback to that base system.

Our analysis showed that the main barriers to large-scale application and diffusion of DTs are social and organisational factors. Our recommendations hence are as follows:

1. Both policy makers, organisations and education/research institutions need to embed the knowledge about DTs into the wider knowledge of digitalisation in general. That means that DTs are seen as one potential tool next to others, all of which use a carefully crafted, managed and multi-applicable data-architecture.

2. Applied knowledge of the applications of DTs (next to applications of other digital technologies) is lacking and that has multiple consequences. Socio-cultural aspects can be more easily considered in the context of specific applications. If these applications are not envisioned yet, then socio-cultural aspects are not taken into account. The same applies for 'standards, laws and regulations' that guide DT development and application to prevent accidents and unwanted consequences.

3. Knowledge of the technology may be deep for those involved with developing the technology, yet the ones deciding about DT use or application may lack that knowledge. Conversely, the ones developing the technology may lack knowledge about its application or about the process of implementing technology so it can be applied. If different types of knowledge are needed (both technological, social and organisational) then in many cases nobody is an 'overall expert' and thus multi-disciplinary collaboration is needed.

Recommendations from Part II - Digital Twins in an Urban Environment

We interviewed professionals in four municipalities about DT development and use.

1. Dutch municipalities have much to learn from each other from their respective digital twin programmes and projects, and more extensive communication and knowledge-sharing is advised. We were surprised by the differences between municipalities. We observed that their points of proficiency vary substantially, and exchanging these points could serve to complement each other and help them arrive at more effective policies and implementations of DTs. After collecting the points of proficiency from the four municipalities, we created an initial audit of 10 points related to DT development and use, which can be used by municipalities.

2. Digital twin development and use in the urban environment is a challenging problem, and treating it as an isolated development within a limited domain or use case may be inappropriate. The technology and its possible use cases can be related to a broad range of individual factors and sub-problems that are inherently connected yet perspective-dependent. This high interrelatedness calls for broad stakeholder involvement across multiple levels by urban actors to form a robust social and political consensus regarding the technology and its use.

3. The development and use of digital twins should be an integral part of the larger digitalisation agenda formulated by municipalities. This agenda often involves a portfolio of complementary activities, some of which are experimental. Some activities may fail, others succeed. This agenda requires a long-term focus, with funding, organisational and political embedding as well as involvement of stakeholders that goes well beyond a simple project approach. Project funding is a starting point but is likely to run dry before the digitalision results are fully implemented and hence more structural funding is required.

4. Digitalisation in general, and digital twins in particular, are tools. It may be wise to combine low-tech solutions if that suffices and high-tech solutions where needed. Applying high-level digital twins is not a goal. All DT applications should be formulated with a stakeholder perspective in mind. For example: citizens and companies would like to have all road and infrastructure maintenance planned integrally, so public spaces do not have to be disturbed multiple times.

Recommendations from Part III - A Look Ahead: Options for the Future

1. For societal and domain-level research, an analysis with digital twin focus or multiple actor-focused analyses can be used to identify possible directions as input for domain-specific or societal scenarios. For an individual actor such as a municipality, a single actor-focused Bounded Dimensions Model can be used to map out and relate current position, barriers, and future ambitions along explicit dimensions to identify risks and possibilities.

2. For insights into digital twins in the context of future norms and values, it is important to consider a broad range of actors. The main bounding effects we see are mostly social and political, simplified into the notion of political bounding. This reflects the integration of norms and values into the development of digital twins in an urban environment. On the level of an individual actor such as a municipality, this forms the bounds of development that can be achieved. However, on a societal level, the combined ambitions of multiple actors may instead reflect the current and upcoming norms and values, and this may lead to a shift in the bounds. We believe this may happen in the near future regarding the aspects of automatic optimisation and management, where the economic and social benefits may in the long term outweigh the current norms and values concerns, and solutions for how to account for aspects such as data security and privacy will be found.

We believe that digital twins as a technology are here to stay for the coming decades, as the complex issues DTs relate to are unlikely to have isolated standalone solutions.

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Appendices

Appendix 1
The Technology Monitor as a Method

The Technology Monitor maps the development and diffusion of a technology. The method consists of three interrelated components:

1. The definition of the technology, to make it clear what it is exactly that is being mapped.
2. The pattern of development and diffusion of a technology, to make it clear how the technology has developed and what its current state is.
3. The system of actors and factors that play an important part in the development and diffusion of the technology, to be able to indicate which factors impede or stimulate the further development and diffusion. This system is also referred to as 'conditions'.

Each of the three components provides a model or simplification of reality and is therefore based on assumptions. The assumptions themselves are not discussed in this brief description.

Definition of a Technology

A technology can be defined on the basis of three aspects:

1. **The technological principle**
2. **The functionality**
3. **The components**

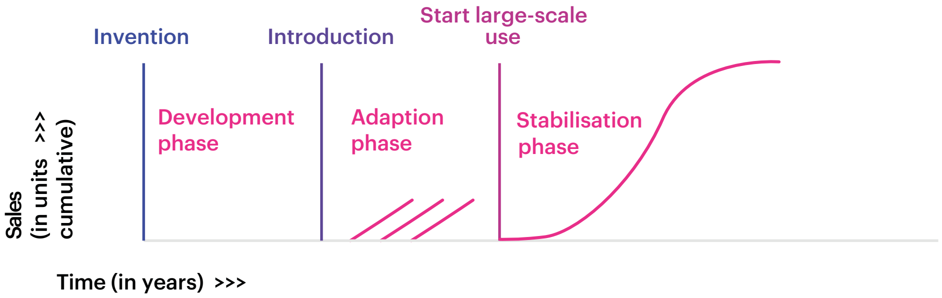
A solar cell is based on the photovoltaic principle (technical principle). It consists of two types of semiconductors close to each other (main components) that, when struck by light or other radiant energy, produce an electrical voltage or current when connected by a conducting wire (extra component). The cell can continue to provide voltage and current autonomously i.e., without an external power source, as long as light continues to fall on the two materials. This current can be used to measure the brightness of the incident light or as a source of power in an electrical circuit, as in a solar power system (functionality).

The technological principle indicates the principle of the operation, the functionality indicates what you can do with the technology and the components make up the basic elements of the technology. See the purple text for an example of a definition of a technology, the solar cell.

Pattern of Development and Diffusion of a Technology

The Technology Monitor by STT contains a model that is a realistic representation of the development and diffusion of a technological breakthrough over time (see Figure A1-1).

Figure A1-1: the more realistic pattern of development and diffusion of technological breakthroughs



In the pattern of development and diffusions, the important moments in time are distinguished:

1. The invention: the first demonstration of the operation of the technological breakthrough.
2. The first market introduction: the first time the technological breakthrough is sold and applied.
3. The start of the industrial production and large-scale diffusion and application of the technological breakthrough.

With these important moments, the three consecutive phases can be distinguished:

1. **The development phase:**
This phase runs from the invention to an initial introduction of products on the basis of the technological invention. The invention is the demonstration of a working principle that is often not yet ready to be manufactured and marketed. In the development phase, research takes place to improve the principle and there are often one or more development trajectories designed to make a product on the basis of the principle that can be sold and applied.

2. **The adaptation phase:**
This phase runs from the first introduction to the start of production and large-scale diffusion of products on the basis of the technology. This phase often involves a trial-and-error process in which different product versions are introduced into various market niches. Adaptation takes place between the product, different customer groups and different applications. That adaptation can ultimately lead to a standard product. Innovation of products, (production) processes and research into improvement of the technology continue as before during this phase.

3. **The stabilisation phase:**
This phase begins with industrial production and large-scale diffusion. It starts with a standard product that can be manufactured on a large scale and that is applied and sold on a large scale. The product versions and applications have at this point stabilised. Often, the innovation of products, processes and research to improve the underlying technology will continue as before.

The *pattern* is a generic model within which, in practice, the length of the phases can vary considerably. The average length of the development phase is about 10 years, and a similar length has been established for the adaptation phase (see Ortt, 2010). Each phase can be skipped or be longer than average. There are technologies where both the development and adaptation phase took only a year (for instance in the case of dynamite) and there are technologies where those phases take a century (for instance in the case of the fax machine). The pattern can stop or be interrupted at every stage. The pattern provides the basis for a large number of scenarios that can occur in practice.

Conditions that Hamper/Stimulate Development and Diffusion

The pattern of development and diffusion of technological breakthroughs provides a *description* of the process of development and diffusion. It does not provide an *explanation* why that pattern takes a specific shape. We are looking in particular for explanations that indicate why the first two phases in the pattern, the development phase and the adaptation phase, sometimes take very little time and sometimes a lot of time.

We have compiled a list of general factors that are needed for the large-scale diffusion of technological breakthroughs. When those factors are in place, they can stimulate the development and diffusion, when they are absent or incomplete, they can be a barrier. The factors are divided into fourteen categories. Seven categories make up the social, economic and technological system: the core factors. The other seven factors can affect the core factors, these are influencing factors that can provide an explanation for the impediment on those core factors. This collection of factors represent a considerable expansion of the factors that Rogers (2010) uses to explain diffusion in the standard innovation-diffusion model. Table A1-1 describes the seven core factors necessary for large-scale diffusion. Table A1-2 describes the influencing factors.

Table A1-1: Core factors for large-scale diffusion of technological breakthroughs

Core factors	Description
1 Product performance	A product (with all components and software) with a sufficiently good performance and quality (in absolute terms or relative to competing products) is needed for large-scale diffusion. A poor performance, poor quality, unintended side-effects from or accidents with products can impede large-scale diffusion.
2 Product price	The price of a product includes financial and non-financial investments (for instance, time and effort) to obtain and use a product. A product (with all its components and software) at a reasonable price (in absolute terms or relative to competing products) is needed for large-scale diffusion. A high price can impede large-scale diffusion.
3 Production system	A production system that can deliver large quantities of products of sufficient quality and performance (in absolute terms or relative to competing products) is needed for large scale diffusion. A lack of such a production system, unintended side-effects, or accidents during production can impede large-scale diffusion.
4 Complementary products and services	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and disposal of products are needed for large-scale diffusion. A lack of or incompatible system components, unintended side-effects from, and accidents with complementary products and services can impede large-scale diffusion.
5 Actors and network formation	Availability of necessary actors and sufficient coordination of the their activities for the development, production, distribution, adoption, use, repair, maintenance, and disposal of products is necessary for large-scale diffusion. Coordination can be emergent or implicit (for instance the market mechanism) or it can be formal and explicit (for instance an industry association). If certain actors or coordination mechanisms are necessary but lacking, that can impede large-scale diffusion.
6 Customers	Customers are needed for large-scale diffusion. Customers must have knowledge of the product and its use, and they need to want to have, be able to afford and want to use the product. If there are no customers, that will impede large-scale diffusion.
7 Standards, rules and laws	Standards, rules, and laws in relation to the product, production, complementary products and services, or how actors (on the supply and demand ends of the market) must handle the product and the surrounding socio-technological system are needed for large-scale distribution. The absence of standards, rules and legislation can impede large-scale diffusion.

The **core factors** make up a complete system surrounding a new technology. If one or more of those factors are absent or incomplete, or if there is insufficient coordination between the factors, that will impede large-scale diffusion.

The **influencing factors** can explain why one or more of the core factors are incomplete, absent or do not fit. As such, these influencing factors explain problems in the system of core factors and give an indication of (future) changes in the core factors. In other words, the influencing factors can explain impediments in the core factors and show changes in those core factors (see Table A1-2).

Table A1-2: Influencing factors for large-scale diffusion of technological breakthroughs

Influencing factors	Description
8 Knowledge of technology	This includes fundamental and applied knowledge of the technology. Fundamental knowledge has to do with technological principles involving the product, production, complementary products and services and knowledge for the development (design), production and management of technological principles. If relevant actors are lacking technical knowledge that is vital to their role, that can impede large-scale diffusion.
9 Knowledge of applications	This includes knowledge of potential applications, knowledge of the market (structure) and the actors involved. This knowledge is needed by all actors, including customers, in order to formulate strategies and product requirements, and to find other actors. If relevant actors are lacking knowledge of applications that is relevant to their role, that can impede large-scale diffusion.
10 Employees and resources	The availability of employees with the necessary knowledge and skills and the availability of resources and input like components and materials are needed for the production and usage of a product, and for production of, complementary products and services. Organisations that play a role in managing these aspects, like trade unions, are also included. A lack of such resources can affect the core factors and thus impede large-scale diffusion.
11 Financial resources	Financial resources and the organisations (for instance banks) or platforms (for instance crowdfunding) to deliver these resources are needed for the development and diffusion of new products, production systems, complementary products and services, and for the adoption, implementation and maintenance of the products. A lack of financial resources among actors on the demand or supply end of the market (two important core factors) can impede large-scale diffusion.
12 Macroeconomic and strategic aspects	Macroeconomic and strategic aspects refer to the general economic situation in a country or industry, like a recession or industry-wide stagnation. Strategic aspects refer to the interests of countries and industries. Macroeconomic and strategic aspects of countries and industries can affect the core factors and thus impede large-scale diffusion.
13 Sociocultural aspects	Sociocultural aspects refer to the norms and values in a certain culture or industry. They include methods and habits in a country or industry and can also refer to interest groups outside of the supply chain. These aspects tend to be less formalised than formal standards, laws, and rules. Sociocultural aspects can influence the core factors and thus impede large-scale diffusion.
14 Accidents and unexpected events	This includes accidents and events outside of the socio-technological system with a major impact, like wars, nuclear accidents, natural disasters and political revolutions. These accidents and events, or the risk of them occurring, can influence the core factors and thus impede large-scale diffusion.

An example indicates why that combination of core factors and influencing factors is so important. If a core factor is missing, for instance because there are no consumers, large-scale diffusion is impossible. Consumers are an important core factor, one that can be influenced by various factors. For instance, consumers can lack knowledge regarding the technology and its applications (influencing factors 8 and 9) or the technology can be too expensive for the consumers (influencing factor 11). Each of the influencing factors has a different effect on the core factor 'consumers' and therefore requires a different policy from regulatory organisations or governments, or a different strategy from organisations wanting to market the technology.

Appendix 2

How to Explore the Status of Core Factors

How do influencing factors affect each of the core factors?

Core factors	Barrier status / Factor status
1 Product performance	NO BARRIER. High-performance sensors, high-speed data connections, high-volume data storage, and computing power for rendering, simulation, AI, and ML are widely available and perform sufficiently well. **Remark 1.1:** Some specific cases may have performance limitations. The understanding of some physical systems that require modelling may be incomplete or of insufficient accuracy, such as in behaviour of structural components under extreme stresses in aerospace technologies.
2 Product price	NO BARRIER. DTs consists of combining established real products with software and networking. **Remark 2.1:** Even though the cost of a DT should be acceptably low in absolute terms, for especially cheap and simple systems, the cost relative to the cost of the base system may be prohibitive. As an example, a DT with sensors, data connections and modelling for a cheap coffee machine vs a DT with sensors, data connections and modelling for an expensive car. **Remark 2.2:** For real products or systems without existing virtual copies to base a DT on, the cost of creating a DT may be prohibitive. As an example, creating a sufficiently representative DT of a concrete bridge from the 1960's may be expensive or even unfeasible because the minimal starting point of detailed CAD/3D models do not exist, and the material specifications may not be known to an accurate enough extent, further complicated by the ageing and wear of the structure since its construction.
3 Production system	NO BARRIER. . The components have established production systems, and software is easily scalable once created. **Remark 3.1:** There may not be a sufficient system in place for creating DTs of real products and systems without a pre-existing basis for a DT (sufficient design and material specifications, as in the bridge example in remark 2.2 above.)
4 Complementary products & services	NO BARRIER. The required complementary services already exist for the required components and software.

Core factors	Barrier status / Factor status
5 Actors & network formation	**BARRIER.** Sufficient networks for development, adoption and use of DT are lacking, since this requires a new level of cross-disciplinary, cross-industrial and cross-institutional coordination hindered by various influencing factors outlined below. **Knowledge of technology:** NOT LIMITING. Sufficient fundamental and applied knowledge of engineering, computation, physics, systems analysis, and innovation management of relevant types exist to support actor and network formation for DTs. **Knowledge of applications:** LIMITING. The knowledge of potential applications is still limited, with focus on industrial product life cycle management and system repair and maintenance. Knowledge of a DT utility in testing and long-term risk management may not be fully realised and can limit additional network formation. For instance, actors involved with building management systems or financial risk management may have understanding applicable to both design, use, and network formation for technologies similar to DTs, but without common understanding of this value, they may not become sufficiently networked. **Employees and resources:** PARTIALLY LIMITING. Employees and resources should not be a limitation for necessary actor & network formation, as this can be already facilitated by existing market actors, among others technology news publications, general technology consultants, networking consultants and software consultants. However, these actors are not yet set into clear roles in networks for the development and implementation of DTs. **Financial resources:** NOT LIMITING. The funds necessary for actor and network formation are in place through both market mechanisms promoting formation of relevant technology businesses, and existing innovation budgets of both businesses and public institutions. **Macroeconomic and strategic aspects:** PARTIALLY LIMITING. In economies with low computer and internet adoption, and low-tech industries and infrastructure networks, actor and network formation for the development, and implementation, DTs may present low additional utility and be of limited interest. This will limit actor and network formation. The reverse is true for economies with high computer and internet adoption and high-tech industries and infrastructure networks. **Sociocultural aspects:** LIMITING. The phenomenon of siloing knowledge and skills within disciplines and institutions can hinder actor and network formation for DTs, because there is inherent resistance to cross-disciplinary and cross-institutional communication by groups and individuals not following open innovation. Furthermore, the lack of a commonly accepted definition hinders communication and can lead to further siloing between fields and their own specific applications of DTs. Accidents and unexpected events: NOT LIMITING. There is no immediately evident influence from accidents or unexpected events to network formation for DTs.
6 Customers	PARTIAL BARRIER. Awareness of the existence and interest in DTs is widespread and growing among potential customers, but many lack a clear vision (including a common definition) of what exactly they want of a DT as a product, limiting development of demand.

Core factors	Barrier status / Factor status
7 Standards, rules, and laws	**BARRIER.** Standards, rules, and laws exist for the components on industrial, ethical, and legal levels, but standardisation of DTs as an individual technology are lacking, both in terms of common definitions, common implementations, and legal frameworks to drive implementation. **Knowledge of technology:** NOT LIMITING. Sufficient fundamental and applied knowledge should exist to support standards, rules, and law formation for DTs. **Knowledge of applications:** LIMITING. The knowledge of potential applications is still limited, with focus on industrial product life cycle management and system repair and maintenance. The focus on already existing use cases may inherently limit development of frameworks and regulations to the initial fields, presenting a barrier to additional applications of DTs. For instance, if risk management in some field such as banking or building fire safety involves strictly defined legal standards and models of evaluation, these may not be adapted easily to allow use of DTs for risk management if the relevant regulators are unaware of the applications of DTs in their field. Another example could be legally mandated car inspections. The use of a DT for a personal car could substantially reduce the utility of regular vehicle inspections, but since cars with DTs and without DTs would still co-exist, entirely new legislation would be required to allow the benefit of DTs in reducing inspection frequency to be realised, and this requires knowledge of the applications of DT among relevant regulators. **Employees and resources:** PARTIALLY LIMITING. The necessary employees and resources to realise development of standards, rules, and laws related to DTs should already exist in the form of standardisation organisations, and regulatory and legislative institutions. However, a lack of such resources can affect the core factors and thus impede large-scale diffusion. **Financial resources:** NOT LIMITING. The financial resources are conditional on the financing of the relevant standardisation organisations, and regulatory and legislative institutions. This should not be a limiting factor in stable environments. **Macroeconomic and strategic aspects:** LIMITING. In economies with low computer and internet adoption, and low-tech industries and infrastructure networks, for actor and network formation for the development, and implementation, DTs may present low additional utility and be of limited interest. Standardisation and regulation development for DTs may then also be of limited interest. The reverse is true for economies with high computer and internet adoption and high-tech industries and infrastructure networks. **Sociocultural aspects:** LIMITING. The phenomenon of siloing knowledge and skills within disciplines and institutions can hinder standardisation and regulation development for DTs, because there is inherent resistance to cross-disciplinary and cross-institutional communication by groups and individuals not following open innovation. DTs are an inherently cross-disciplinary technology and would require coherent regulation from multiple public bodies in different fields. As a hypothetical situation, there could be competition between multiple regulatory bodies all with a stake in DTs to fully "own" the regulation of DTs, such as traffic safety, building safety, or banking regulation. This may then lead to siloing by the competing regulators, leading to certain fields taking precedence over other fields. Furthermore, the lack of a commonly accepted definition hinders communication and can accentuate this regulatory siloing further, hindering the formation of standards and regulation for cross-disciplinary application of DTs. **Accidents and unexpected events:** LIMITING. Negative events with industrial products and systems that would be fruitful for the proliferation of DTs such as autonomous vehicles can create regulatory hindrance. For instance, disallowing autonomous vehicle control due to accidents under high public scrutiny could limit the extent to which the DT of the vehicle can act as a control system. Restrictive data management and privacy rules could likewise hinder the development of legislation needed for unhindered use of DTs.

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