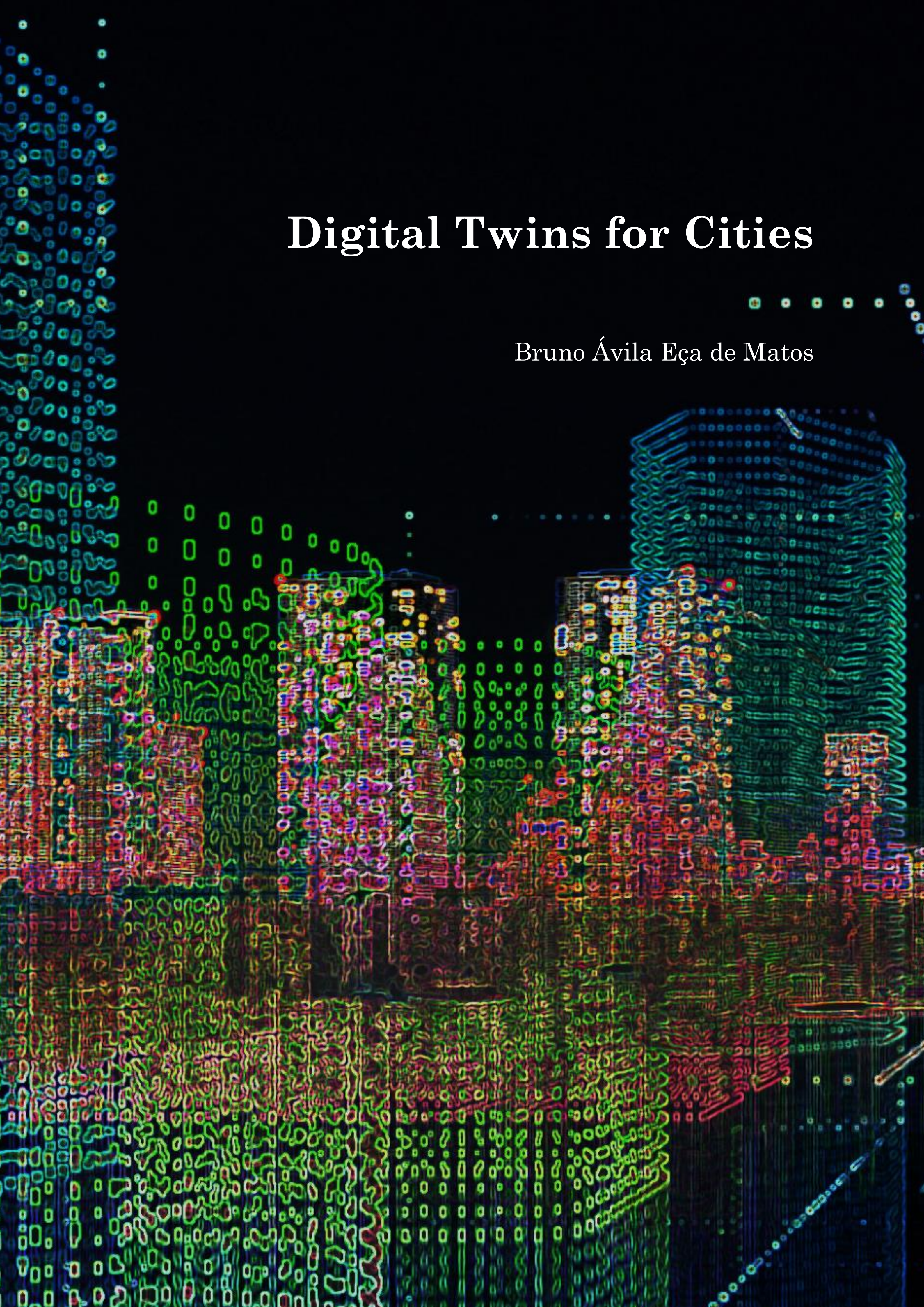
Digital Twins for Cities

Digital Twins for Cities

Bruno Ávila Eça de Matos



EINDHOVEN UNIVERSITY OF TECHNOLOGY
Stan Ackermans Institute
SMART BUILDINGS & CITIES

DIGITAL TWINS FOR CITIES

By

Bruno Ávila Eça de Matos

A thesis submitted in partial fulfillment of the requirements for the degree of Engineering Doctorate (EngD), on account of the decision of the Thesis Evaluation Committee, defended on Monday, the 15th of May 2023 at 15:00 hours.
The research described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct.

Thesis Evaluation Committee:

Prof. Dr. Bauke de Vries, scientific supervisor
Dr. Gamze Dane, scientific co-supervisor
Tom van Tilburg, company advisor
Dr. Dujuan Yang, first independent member
Prof. Dr. Henk Scholten, second independent member

Eindhoven, the Netherlands

This thesis has been established in collaboration with

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Geodan part of LOCATIQS Group

A catalogue record is available from the Eindhoven University of Technology Library

SAI-report: 2023/031

ABSTRACT

Digital twins are increasingly recognized as valuable instruments in urban planning and management, transforming how we create, manage, and enhance human settlements. Although becoming more popular and acknowledged, there is still limited agreement on their definition and requirements within the built environment, as well as the complexities tied to their application at city level. This Engineering Doctorate research project endeavors to bridge this gap in knowledge by delivering a comprehensive understanding of digital twins and formulating precise guidelines and methodologies for their implementation.

Initiating with a literature review, the thesis examines existing frameworks and concepts concerning the implementation of digital twins. This examination lays the foundation for comprehending the essential elements and factors needed for efficient digital twin development. Following this, a global quantitative assessment of over three hundred digital twins at diverse spatial scales is carried out, spanning large infrastructure, districts, cities, and regions. This assessment reveals the current state of digital twin technology and its uses, identifying effective practices and areas demanding further attention.

To gain deeper insight into the connections between stakeholders in the digital twin ecosystem, the thesis features an extensive case study of the Netherlands. This research uncovers valuable information about the roles and interactions of different stakeholders in digital twin development and utilization, as well as the distinct challenges and opportunities present in this rapidly evolving domain. Conclusively, the project proposes a methodology for implementing digital twins at city level. This comprehensive framework addresses the technical, social, and organizational dimensions of digital twin development, offering practical direction for city officials, policymakers, and other stakeholders eager to fully explore the benefits of digital twins for cities.

Keywords: *digital twins*, *smart cities*, *urban intelligence*, *innovation ecosystem*.

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1 Introduction

1.1 Background

In the current context of urban planning and management, city officials and stakeholders are confronted with an increasingly complex set of challenges. The complexity and uncertainties linked with climate change are arguably the most significant challenges that urban planners have ever faced (Susskind, 2010). The need for resilience in the face of climate change has become a pressing concern, as cities must adapt to rising sea levels, more frequent and severe weather events, and shifting resource availabilities (Revi et al., 2014). Additionally, rapid urbanization is placing immense pressure on urban infrastructure, housing, and public services, as cities strive to accommodate growing populations and the associated demands on resources (United Nations, 2018). Furthermore, social inequalities persist and, in some cases, are exacerbated within urban environments, necessitating inclusive policies that promote equity and improve access to essential services, such as education, healthcare, and employment opportunities (Marcotullio et al., 2013).

The use of digital tools has the potential to significantly improve city planning and management in response to these complex challenges. By leveraging data-driven insights, city officials can make more informed decisions regarding urban development and resource allocation, enhancing the resilience and sustainability of urban environments. Planning support systems, for instance, can be applied at various scales for a range of urban challenges, making use of the variety, visualization and value of big data (Pettit et al., 2018). Enabling the simulation of various scenarios, digital tools enable decision-makers to evaluate the potential impacts of different interventions, such as climate adaptation measures, infrastructure upgrades, and social programs, even before they are implemented. This capacity for data-driven decision-making leads to more efficient planning processes, ultimately creating more resilient and equitable cities.

Furthermore digital tools can be used to facilitate collaboration and communication among various stakeholders, fostering more inclusive approaches. Through the use of inclusive and responsible technological solutions, city officials, planners, residents, and other stakeholders can engage in meaningful dialogue and co-create solutions that address the diverse needs of urban populations. By promoting transparency, accountability, and public participation, digital tools can help bridge the gap between decision-makers and citizens, leading to more equitable outcomes and the development of cities that are better equipped to navigate the challenges of climate change, rapid urbanization, and social inequalities.

Digital twins have been gaining prominence in the world of engineering and technology since their inception in the early 2000s. The term "digital twin" was coined by Michael Grieves at the University of Michigan in 2002, referring to a virtual replica of a physical asset, system, or process that enables real-time monitoring, analysis, and optimization (Grieves, 2014). The development of digital twins has been greatly influenced by advances in information and communication technology, including the widespread adoption of Internet of Things (IoT), big data, and cloud computing (Tao et al., 2018). Fig 1-1 below presents an example of this new framework digital twin-based design. It considers virtual and physical factors, in three phases of product development: conceptual design, detailed design and virtual verification.

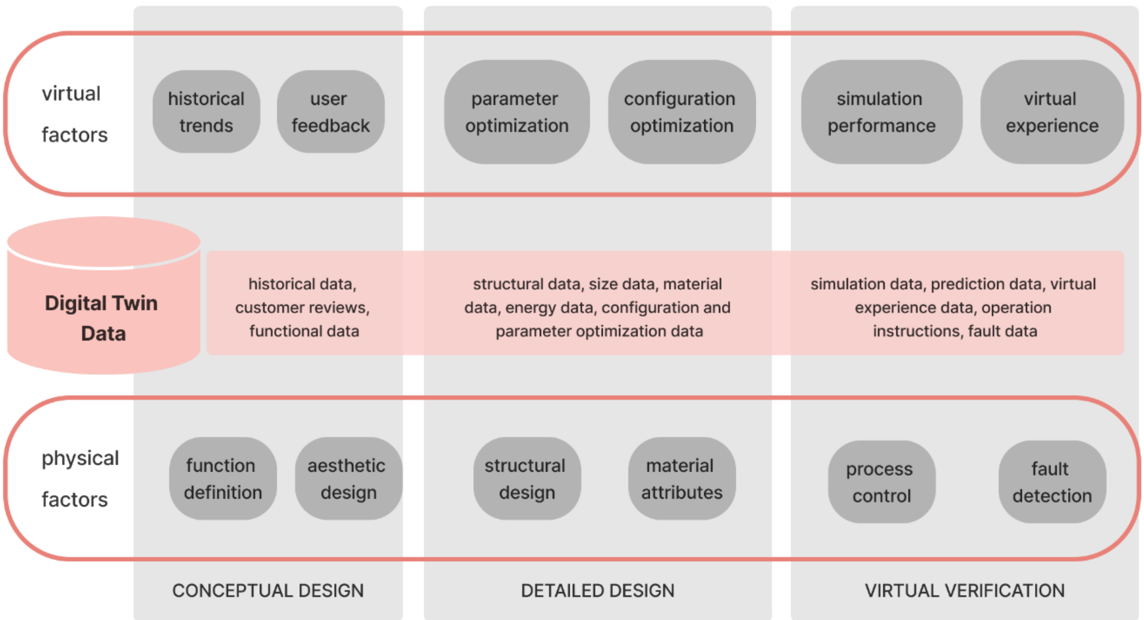


Fig. 1-1: Digital twin-based product design. Source: Adapted from Tao et al., 2018.

In the context of the Fourth Industrial Revolution, also known as Industry 4.0, the application of digital twins has expanded in recent years beyond traditional manufacturing and industrial settings, penetrating various sectors such as aerospace, healthcare, energy, and transportation (Rosen et al., 2015). Defining a digital twin as "a software design pattern that represents a physical object with the objective of understanding the asset's state, responding to changes, improving business operations and adding value", Gartner (2019) affirms that digital twins are entering mainstream use, with over two-thirds of companies that have implemented IoT deploying at least one digital twin in production by 2022.

The potential of digital twins for the built environments was first explored at the scale of buildings in recent years, as a further development of Building Information Modelling – BIM. According to Davila Delgado & Oyedele (2021), "only two documents are listed in Scopus for 2016 when searching for the terms "Digital Twin" and "building", while, 178 documents are listed for 2020". These pioneering efforts opened the way for digital twins at the urban scale, further explored in the next section.

1.2 Definitions

The growing interest in digital twins for urban environments led to the development of several interrelated concepts that reflect the diverse range of applications and scales at which digital twins can be deployed. This section elaborates on current similar concepts: *(geo)spatial digital twins*, *urban or city digital twins* and *city-level digital twins*.

(Geo)spatial digital twins refer to the virtual replica of a territory based on georeferenced information. These virtual replicas encompass various spatial components, such as buildings, infrastructure, and natural features, and are typically built using geographic information systems (GIS), 3D modeling, and remote sensing technologies. Spatial digital twins enable dimensional, location-based representation of assets and systems, providing a foundation for visualizing and analyzing data, enabling stakeholders to better understand the physical landscape and its interactions with human activities (WGIC, 2022b). Fig. 1-2 below positions digital twin use cases on a dimensional accuracy and spatial positioning matrix, placing *smart cities* and smart infrastructure on the second more complex tier, revealing the need for high geometric integrity and location accuracy in these use cases.

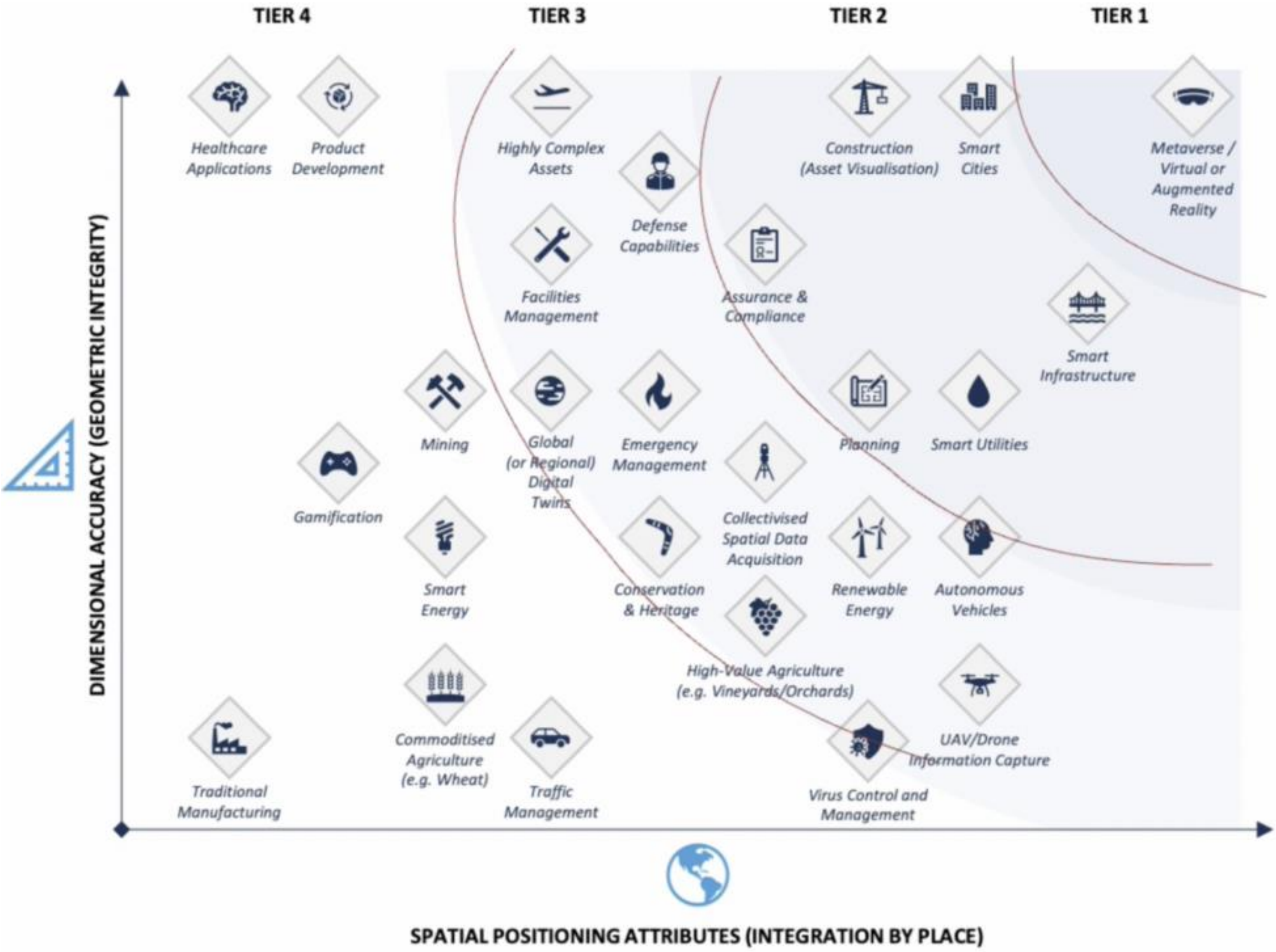


Fig. 1-2: Dimensional-spatial matrix for digital twins. Source: (WGIC, 2022a).

The terms *urban digital twins*, *city digital twin*s and *city-level digital twins* and have been used interchangeably in many papers and reports, defining models of urban environments or urban infrastructure, making use of data from the real world for monitoring or simulations (Ferré-Bigorra et al., 2022). Using commercial solutions or own software, these digital twins combine on data platforms spatial city geometry with information on transportation systems, utilities, environmental conditions, and socio-economic factors, creating a holistic representation of the urban environment.

The variety of urbanization processes in different places of the globe led to a myriad of different urban patterns. While some countries like the United States have a clear distinction between urban and suburban environments, called cities and towns respectively, with different population density and even government structures. In other regions a clear boundary can be established between urbanized and rural areas, like in most of Latin America. In densely populated countries like India, this boundary is far from clear, and the term *human settlement* is more popular among urbanists. This is why the use of the terms *urban* and *city* can lead to different understandings also when discussing digital twins.

The complexity of the regional scale, including the built environment and natural areas, means that *digital twins of the built environment* do not always match the virtually replicated geography. In common, all these digital twins have somewhat of a spatial component, but the smaller importance of high location accuracy for some digital twins, like the ones used for transportation planning and economic development, makes it harder to include them all under the umbrella of *spatial digital twins*.

For the purpose of this thesis, the term *digital twin* refers to a virtual replica at larger spatial scale, namely everything between districts and large infrastructure systems to cities and regions, aiming at the representation of processes and elements with direct impact to human settlements and their population. The reasoning behind this choice is that these digital twins have a similar degree of technological and governance complexity. Digital twins of buildings and single infrastructure elements, like bridges, as well as digital twins of the Earth are thus not in the scope of this research.

1.3 State of the art and research gap

The application of digital twins in urban environments has gained significant impulse in recent years, with several studies exploring how they contributed to specific use cases. However, the current state of the art reveals a predominant focus on the qualitative case approach, wherein researchers examine specific instances of digital twins and assess their impact on urban planning, infrastructure management, and other relevant domains. While these case-based studies provide valuable insights into the practical applications of digital twins, they often lack a comprehensive understanding of the broader implications tied to implementation in the context of government.

The research gap in the field primarily lies in the limited exploration of the quantitative data approach, especially due to the limited number of digital twin initiatives mapped by academic papers. This research opens up to actively identify and also include less documented projects all over the world, which enables a more systematic analysis of the various attributes, factors, and challenges associated with digital twins. By shifting the focus from individual use cases to a data-driven perspective, this research uncovers patterns, trends, and relationships that may not be readily apparent in the context of isolated implementations.

Moreover, the existing literature tends to concentrate on the technological aspects of digital twins, often overlooking the importance of human-centered approaches and the complexity of the engagement of various stakeholders in the development and deployment of digital twin initiatives at the city and regional scale. By addressing these gaps, research can provide a more holistic understanding of the potential of digital twins in shaping the future of urban planning and governance, as well as offer practical guidance for city officials and other stakeholders in the implementation of digital twin initiatives.

1.4 Research Aim and Questions

The primary aim of this research is to address the identified gaps in the current state of the art by providing a comprehensive, data-driven analysis of digital twins. This study seeks to move beyond the use case approach that dominates existing literature, offering clear guidance for city officials and other stakeholders in the development and deployment of digital twin initiatives in different contexts. To achieve this aim, this thesis addresses the following key research questions:

a) How can digital twins effectively support the planning and management of large infrastructure, districts, cities and regions? By examining the quantitative data associated with digital twins, this study uncovers patterns and trends that can inform the design, implementation, and evaluation of large-scale digital twin initiatives. This analysis helps us identify the most promising applications of digital twins, as well as the factors that contribute to their success in supporting data-driven decision-making.
b) How to overcome the challenges in the implementation digital twin initiatives at the municipal and regional level? Drawing on a global assessment of digital twins, this research will explore the various attributes, factors, and challenges that influence the effectiveness of digital twin initiatives. This analysis will include an investigation of the technological, organizational, and socio-economic dimensions of digital twin implementation, as well as the importance of stakeholder engagement and human-centered approaches in proposed steps for successful implementation.

By addressing these questions, the study aims to provide valuable insights and practical recommendations for city officials, planners, policymakers, and other stakeholders involved in the development of digital twin initiatives. By doing so, this research contributes to the advancement of knowledge in the field of digital twins, and will ultimately help shape the future of urban planning and city governance.

1.5 Relevance

The relevance of this research lies in its potential to contribute to both the scientific and societal understanding of digital twins in large-scale environments. By adopting a data-driven approach and moving beyond the prevalent use case studies, this thesis sheds light on the broader implications and opportunities associated with the implementation of digital twin initiatives.

From a scientific perspective, the research enhances the current knowledge base by systematically examining the quantitative data related to digital twins in urban contexts. This will enable the identification of patterns, trends, and relationships that can inform future studies and guide the development of new theoretical frameworks and methodologies. The insights gained from this research will be valuable not only for scholars working in the field of urban planning and digital twinning but also for researchers in related disciplines, such as computer science, geography, and public administration.

From a societal standpoint, the research offers clear guidance for city officials and other stakeholders involved in the development and deployment of digital twin initiatives. By providing a comprehensive understanding of the various factors, challenges, and best practices associated with digital twinning, this study will help decision-makers design and implement more effective strategies for addressing complex urban issues. As a result, the research has the potential to generate awareness within and outside city government, fostering greater collaboration among different stakeholders in the pursuit of sustainable urban development.

Furthermore, the research contributes to the ongoing discourse on the role of innovation in shaping the future of cities. As digital twin technology continues to evolve, it is essential to understand its potential applications and limitations, as well as the factors that influence its adoption and impact. By offering key quantitative insights into these aspects, this thesis will help bridge the gap between scientific research and real-world practice, ultimately contributing to the development of more resilient and equitable cities and regions.

1.6 Research Methodology

To address the research aim and questions, this study makes use of a combination of research methods that will provide a comprehensive understanding of digital twins. As illustrated on Fig. 1-3, the following methods are employed:

a) *Literature Review*: A review of existing literature on digital twin frameworks and human-centered digital twinning is conducted. This review covers both academic and industry sources, as well as a few case studies, to identify the current state of the art and research gaps. The literature review also provides the theoretical foundation for the research, helping to refine the research questions and guide the subsequent stages of the study.

b) *Global Assessment*: A global assessment of the many attributes of digital twins is conducted, drawing on primary quantitative data manually extracted from documentation coming from various sources, such as academic publications, industry reports, company websites and governmental portals. This assessment involves the analysis of key factors, challenges, and best practices associated with digital twinning at the city level, enabling the identification of patterns, trends, and relationships that can provide answers to the research questions.

c) *Local Digital Twin Ecosystem Assessment*: A detailed assessment of the digital twin ecosystem in the Netherlands is carried out, focusing on the providers, users, use cases, and other relevant aspects of digital twinning in the country. This assessment is based on the collection and analysis of primary and secondary data, such as interviews, surveys, and document analysis, to provide a comprehensive understanding of the Dutch digital twin landscape.

d) *Steps for Digital Twin Implementation*: Based on the findings from the literature review, global assessment, and detailed assessment of the Dutch ecosystem, a set of practical steps for the implementation of digital twin initiatives in urban environments is developed. These steps are informed by the identified patterns, trends, challenges, and best practices, and provide clear guidance for city officials and other stakeholders involved in the development and deployment of digital twin initiatives.

By employing this multi-method approach, the research generates a comprehensive, data-driven understanding of digital twins in urban environments, addressing the identified gaps in the existing literature and providing valuable insights for both scientific and societal stakeholders.

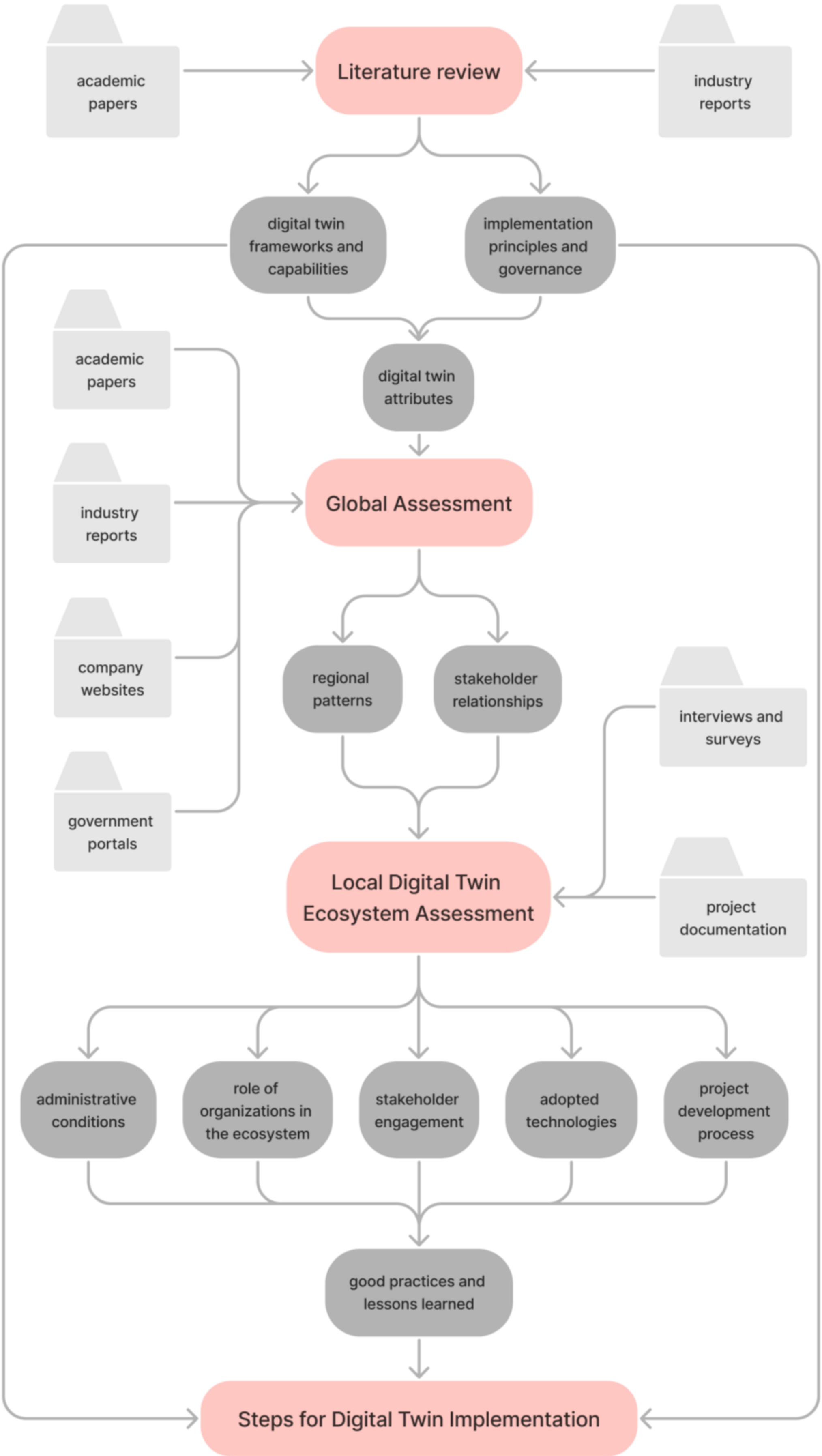


Fig. 1-3: Thesis Research Methodology.

1.7 Structure of the thesis

In addition to this introduction chapter, the thesis is structured into five chapters, each addressing a specific aspect and phase of the EngD research, as follows:

a) *Literature Review*: this chapter presents a comprehensive review of existing literature on digital twin frameworks and human-centered digital twinning, summarizing the current state of the art, identifying research gaps, and establishing the theoretical foundation for the study.
b) *Global Assessment of Digital Twins*: in this chapter, the methods and findings from the global assessment of digital twins are presented, highlighting key patterns, trends, factors, challenges, and best practices associated with digital twinning at the city level. This analysis informs the research questions and contribute to the development of the digital twin implementation steps.
c) *Digital Twin Ecosystem in the Netherlands*: this chapter details the results of the in-depth assessment of the digital twin ecosystem in the Netherlands, offering insights into the providers, users, use cases, and other relevant aspects of digital twinning in the country.
d) *Strategic Methodology of Digital Twin Implementation at the City Level*: Based on the findings from the previous chapters, this chapter outlines a set of practical steps for the implementation of digital twin initiatives in urban environments. These steps will provide clear guidance for city officials and other stakeholders involved in the development and deployment of digital twin initiatives.
e) *Conclusion*: the final chapter synthesizes the main findings of the research, discusses their implications for both scientific and societal stakeholders, and provides recommendations for future research in the field of urban digital twins.

By following the abovementioned structure, this thesis presents a coherent and comprehensive examination of digital twins in large-scale environments, addressing the research aim and questions, and contributing valuable insights to the scientific and societal understanding of the process of digital twinning at the city level.

1.8 References

Davila Delgado, J. M., & Oyedele, L. (2021). Digital Twins for the built environment: learning from conceptual and process models in manufacturing. *Advanced Engineering Informatics*, *49*. https://doi.org/10.1016/j.aei.2021.101332

Ferré-Bigorra, J., Casals, M., & Gangolells, M. (2022). The adoption of urban digital twins. *Cities*, *131*. https://doi.org/10.1016/j.cities.2022.103905

Gartner. (2019, February 20). *Gartner Survey Reveals Digital Twins Are Entering Mainstream Use*. Https://Www.Gartner.Com/En/Newsroom/Press-Releases/2019-02-20-Gartner-Survey-Reveals-Digital-Twins-Are-Entering-Mai.

Grieves, M. (2014). Digital Twin : Manufacturing Excellence through Virtual Factory Replication. *White Paper*, *March*.

Marcotullio, P. J., Sarzynski, A., Albrecht, J., Schulz, N., & Garcia, J. (2013). The geography of global urban greenhouse gas emissions: An exploratory analysis. *Climatic Change*, *121*(4). https://doi.org/10.1007/s10584-013-0977-z

Pettit, C., Bakelmun, A., Lieske, S. N., Glackin, S., Hargroves, K. 'Charlie,' Thomson, G., Shearer, H., Dia, H., & Newman, P. (2018). Planning support systems for smart cities. *City, Culture and Society*, *12*. https://doi.org/10.1016/j.ccs.2017.10.002

Revi, A., UK, D. S., Aragon, F., Corfee-Morlot, J., Kiunsi, R. B. R., UK, M. P., Roberts, D., Solecki, W., Balbus, J., Cardona, O.-D., & others. (2014). Urban areas. In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In *Context* (Vol. 8). https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap8_FINAL.pdf

Rosen, R., Von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *IFAC-PapersOnLine*, *28*(3). https://doi.org/10.1016/j.ifacol.2015.06.141

Susskind, L. (2010). Responding to the risks posed by climate change: Cities have no choice but to adapt. *Town Planning Review*, *81*(3). https://doi.org/10.3828/tpr.2010.5

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *International Journal of Advanced Manufacturing Technology*, *94*(9–12). https://doi.org/10.1007/s00170-017-0233-1

United Nations. (2018). World Urbanization Prospects: The 2018 Revision. In *Economic and Social Affairs* (Vol. 54, Issue 10). https://www.un-ilibrary.org/content/books/9789210043144

WGIC. (2022a). *Spatial Digital Twins: Global Status, Opportunities, and the Way Forward*. https://wgicouncil.org/wp-content/uploads/reports/WGIC-Policy-Report-2022-01-Spatial-Digital-Twins-2.pdf

WGIC. (2022b, November 4). *Spatial Digital Twin Technology Framework and Use Cases*. Https://Wgicouncil.Org/Spatial-Digital-Twin-Technology-Framework-and-Use-Cases/.

2 Literature Review[1]

This section delves into a comprehensive literature review exploring the framework for digital twins and its social dimensions, with an emphasis on international standards and guidelines related to implementation and governance models. The review considers the interactions between digital twins and local stakeholders, including community engagement, city management, technological aspects, and potential opportunities. The objective is to identify crucial aspects that emerge when digital twinning cities within complex governance environments, while maintaining a strong focus on the active role of citizens.

2.1 Digital twin frameworks and capabilities

Applying existing cutting-edge technology from other fields to meet the complexity requirements of designing, planning and managing cities is a condition to be met by city officials in the context of climate change, rapid urbanization and social inequalities. The application of these solutions relies on geographic information systems and data coming from plenty of different sources when a model intends to twin a large-scale environment. Researchers from academia and the public sector have been studying this field to provide clear frameworks for digital twin development.

According to Batty (2018) the idealization of having digital twins and reality as identical twins will never be achieved, but the main quest in city modelling would be to link the functional environment (i.e. human behavior, preferences) and the physical urban environment to socio-economic processes in cities. The author claims there are three different types of digital twins, also called families of simulation models for urban analytics (illustrated in Fig. 2-1):

[1] This chapter was partially published by the author on 6 Oct 2021 at Geodan Research Blog with the title *Digital Twin Frameworks*. It is accessible at https://research.geodan.nl/digital-twin-frameworks/.

- Physical representation of the elements that define the buildings in the city – building in digital representation, VR, AR and thence BIM. The Virtual London Platform, ViLo, is one example of twin in this sense.
- Realtime models, e.g. traffic, supply and demand, logistics. This could be extended to real time dynamic data in general, or the *high frequency city* as Batty calls it. The simulations undertaken by London's metropolitan transportation authority in order to improve service would be one instance of this kind of twin.
- Long-term change models, the so-called *low frequency city* simulating urban growth and change. The QUANT model uses spatial analytics to reconstruct and preview phenomena such as the impact of wages in housing prices at the regional scale.

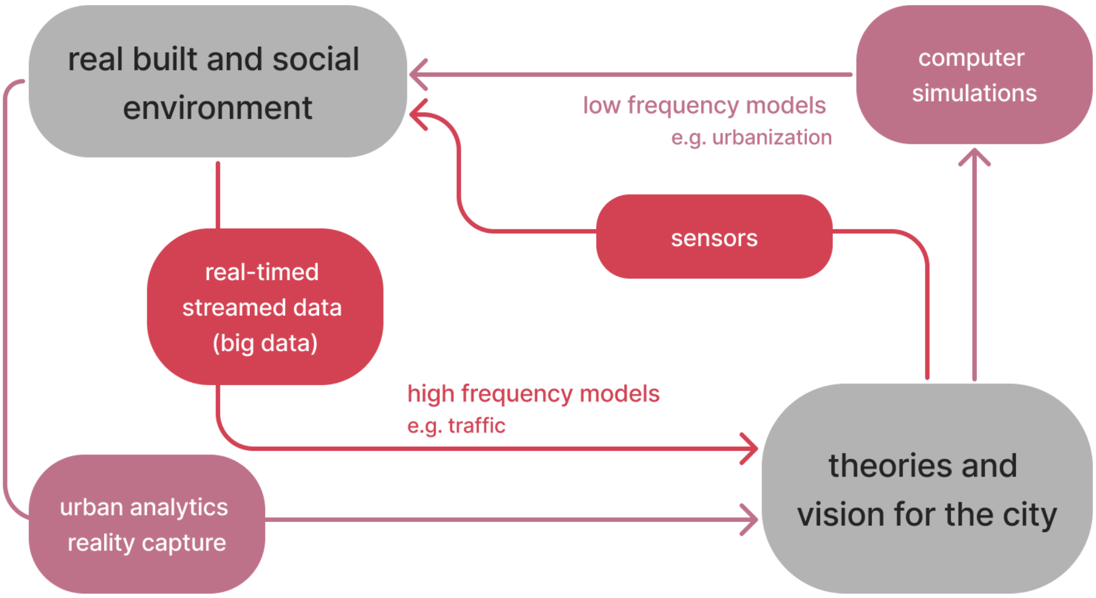


Fig. 2-1: Smart City Diagram. Source: Adapted from Batty (2020).

Castelli et al. (2019) developed the Urban Intelligence - UI paradigm, which proposes a framework which defines a structure for the digital version of the city, defined as the cyber-physical counterpart of all the city systems and sub-systems. The main characteristics of its architecture are: full multidisciplinary integration of city layers, constant connection and evolution, integration of participative strategies to include human-oriented information and modularity of application.

Fig. 2-2 below illustrates the UI architecture proposed by Castelli et al (2019). This paradigm aims at creating a unified multidisciplinary approach, rather than solving specific problems. The items in this architecture are further explained below:

- *City Knowledge Models*: The design and development of the city model takes place in the start-up phase of the platform construction: capitalizing on data provided by cartography, laser scans and other methods, data layers of interest can be collected and indexed, making them easily accessible by services in the UI platform. The 3D data is used beyond visualization, since simulations and numerical methods may require knowledge about the entities, like using them as boundary conditions, for example. It must be precise enough so metrics can be extracted automatically from the 3D model, requiring no physical measurements. Metrics for evaluating the status of each relevant city sub-system can be defined along with computational methods to evaluate them on the digital twin.
- *Data Collection*: This module is designed to acquire data arising from (a) the network of sensors, mainly densely deployed low-energy devices, (b) participatory tools such as apps and questionnaires to get input from citizens and (c) intelligent actuators acting on the city system according to the solutions design by the other modules of the platform.
- *Data Lake and ICT Platform*: An ICT platform that must store, manage, access and analyze the data collected. The data lake concept refers to organizing a large amount of data (in native format, formatted or output of processes) for documentation, visualization, data analytics and knowledge acquisition. It has the data as a static component and a dynamic component to provide the functionalities necessary to manage and exploit these data. The platform is useful by support the management of all the sub-systems of the urban organism.
- *Modelling and Simulations*: The sense-reason-act loops are exploited by different technologies to simulate the subsystems of the city, for example advanced machine learning, well-defined mathematical structures or more basic calculations. The idea is that due to the complexity of the city system, many different solutions can be adopted, developing a number of special purpose controllers.

- *City Digital Twin and Decision-Making via Multidisciplinary Analysis and Optimization*: Modeling and simulation tools provide data-driven, physics-based and assimilated models for each disciplinary domain. The Multidisciplinary Analysis (MDA) provides integration of all modules. The optimization is applied to double-proof the solutions, reconciling different approaches in coordinated efforts able to cope with heterogeneity. The core of the twinning process is achieved by integrating the City Knowledge Model with simulation tools.

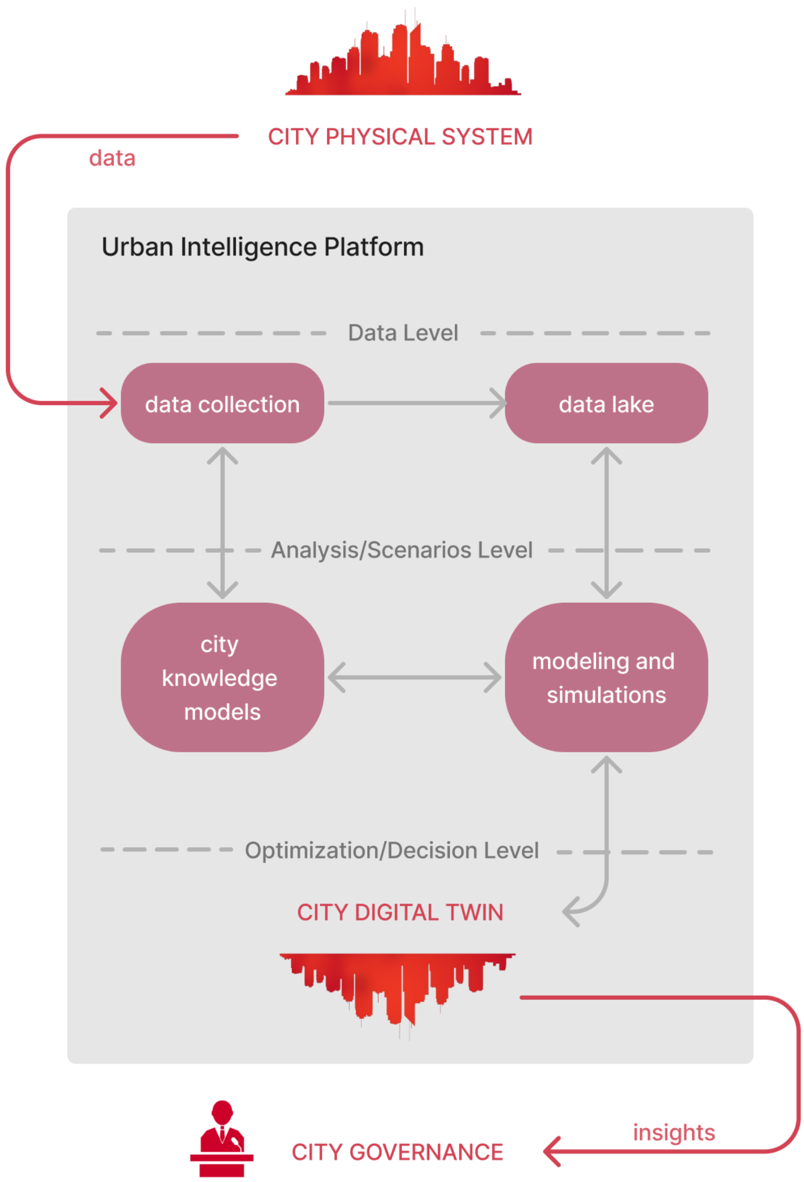


Fig. 2-2: Proposed architecture for Urban Intelligence. Source: Adapted from Castelli et al (2019).

For Woods & Freas (2019), the rise of digital twins for the built environment is a direct result of the confluence of pressing real world challenges and new technologies, such as: (a) new sensors with real-time data transmission monitoring assets and processes that were previously invisible; (b) machine learning and artificial intelligence can analyze vast data sources providing insights for decision-maker; (c) perfectioned dynamic simulation modelling; (d) visualization tools that bring complex datasets to life, also enabling new forms of stakeholder engagement.

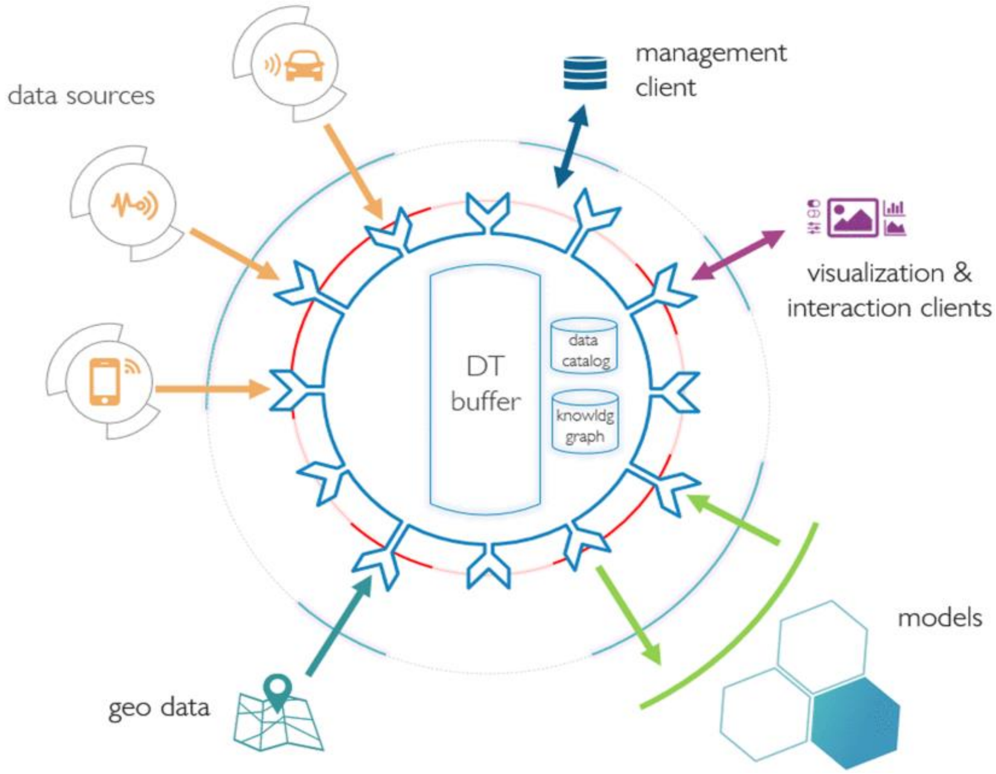


Fig. 2-3: DUET's T-Cell architecture. Source: Raes et al. (2022).

In the scope of the Digital Urban European Twins - DUET research project, Raes et al. (2022) propose a new framework for digital city twins illustrated on Fi.g 2-3 above. Named T-Cell, this framework acts as a container for models, data and simulations, making the information flow from diverse static, historic, open and real-time data sources, translating it into usable output and insights for decision-makers. According to this framework, digital twins rely on three essential building blocks for effective functioning:

a) relevant and purpose-driven *models for the physical elements* being examined, balancing detail with usability.

b) *evolving data* to account for changes in conditions like traffic, air quality, and noise levels, enabling a more comprehensive understanding of systemic shifts over time.

c) *dynamic updates* linked to simulation models, ensuring synchronization with the ever-changing physical environment.

For the Centre for Data Leadership (2020), the digital twin can be defined by its basic capabilities in feeding live data flows from a physical or natural asset. Table 2-1 below presents the functions and capabilities that would need to be offered as a minimum by digital twins.

Table 2-1: Basic capabilities of digital twins. Source: Centre for Data Leadership (2020).

Function	Capability
Connect	There must be a live connection between the digital replica and the physical world.
Integrate	Intelligently checks and links relevant data from different sources (and across sectors).
Visualize	Display multisource data to the user. This allows access to the information users need across the whole asset operation lifecycle.
Analyze	Federated datasets from various sources can be processed, modelled, analyzed and simulated.
Secure	A security-minded management approach to data and information by applying adequate security and privacy standards.

Meta et al. (2021) utilize Camp Nou Stadium in Barcelona as a testing ground for *City Physiology*, a theoretical framework for urban digital twins. By examining the framework's modularity and adaptability on a large-scale facility, this case study demonstrates its potential beyond city-scale simulations. The proof of concept involves coupling statistical techniques with an agent-based simulation platform to model a crowd in the stadium, following a four-step process to construct the case study. Both conceptual (interdomain) and technical (domain-specific) layers of the digital twin are defined and interconnected in a nonlinear manner, reflecting the complexity of the simulated object. The outcome illustrated on Fig. 2-4 below presents a strategy for developing digital twins from a domain perspective, laying the groundwork for more intricate and ambitious simulators.

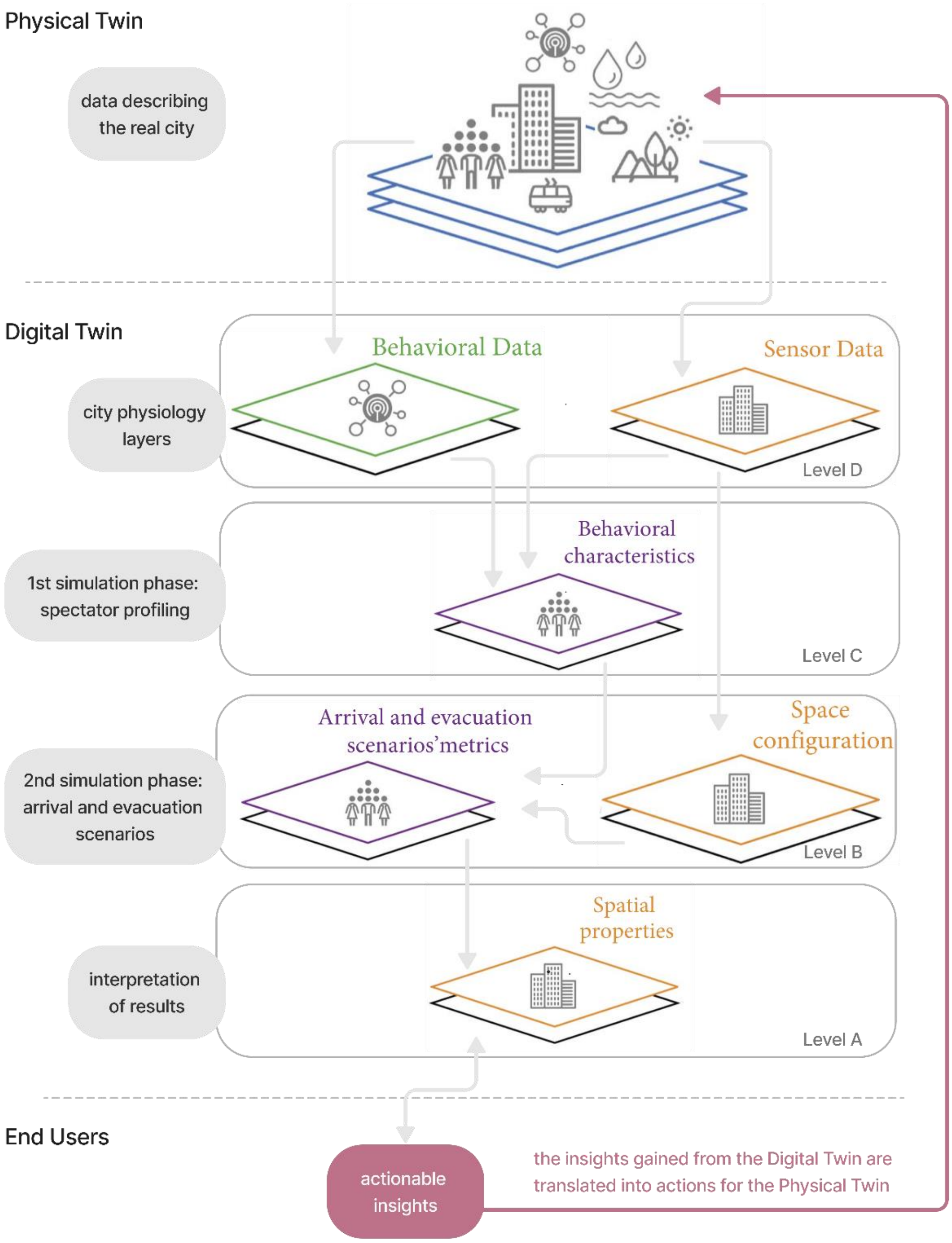


Fig. 2-4: City Physiology Modular Framework. Source: Adapted from Meta et al. (2021).

For Griffith & Truelove (2021), a digital twin is composed by some generic components defined as follows: (a) data, that can be spatial, statistical or streamed from IoT devices; (b) data services, which transform and prepare data sources so they are fit for purpose for the use in a digital twin platform, like converting to different file formats, making data accessible or providing access to authorized users; (c) platforms/applications enabling visualization, analytics or workflow, supporting decision and control systems and (iv) use, where digital services are consumed by the end users. The authors also established some categories of roles that entities can play in the digital twin ecosystem. An organization or group of organizations can occupy one or more of these roles depending on its expertise, institutional mission or legal jurisdiction:

a) *digital twin platform/application operator*: responsible for developing, operating and maintaining a digital twin platform or application.
b) *digital twin data service provider*: provides digital twin data services to data custodians or digital twin platform operators.
c) *digital twin data custodian*: collects, generates, maintains data for the purpose of carrying out their functions.
d) *digital twin data user*: end-user of the digital twin platform, which are able to draw insights and decision support about issues of interest.
e) *digital twin stakeholder*: could be impacted by the digital twin, either in connection with the supply and use of data that could be personal or confidential.

Griffith & Truelove (2021) defined six maturity levels for spatially-enabled digital twin initiatives as presented in Fig. 2-5. The benefits arising from digital twin implementation depend highly on their evolving maturity. For the authors, even in earlier levels of maturity the initiative can provide significant value. Another relevant aspect is the level of collaboration, openness, adoption of common standards and data sharing with other digital twins, but it also depends on the development of the whole field of digital twinning. The success of digital twins in Australia in delivering public value would depend, for them, on the ability of data custodians to easily release or share their data. This ability could be assessed in a maturity level in itself, divided in three phases: (a) *adhoc* data release and sharing, while most data sharing initiatives is led by enthusiasm from government agencies by point-to-point arrangements; (b) systematized data sharing, when there are legislation or mandates for data sharing between entities; (c) networked data management, the most advanced phase, when data sharing involves all four sectors of the quadruple helix (government, academia, companies and community) and is driven less by legislation and more by the internal benefits or public value. The dominant model for data sharing in networked data management is based on federated arrangements.

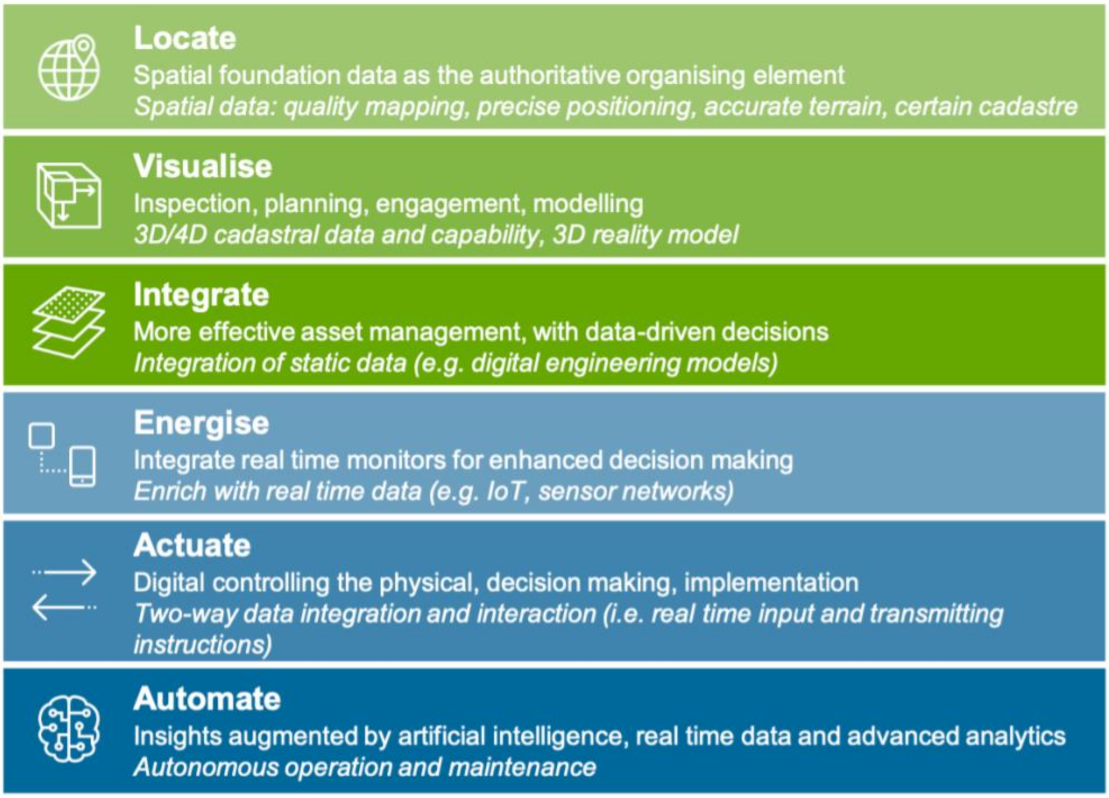


Fig. 2-5: Spatially-enabled digital twin maturity model. Source: Griffith & Truelove (2021).

The federated model for data sharing is the most flexible and scalable approach to support the required level of data sharing and collaboration. In this model, data is exchanged on a coordinated basis between agencies based on the use of standards and/or shared platforms that can process and transform data, like API gateways and data linkage, while retaining the central role of the data custodian in managing their data and enabling data sharing. Its major challenge is that it requires a cross-agency/organization agreement on standardized processes about data quality, metadata, data sharing agreements as coordinating infrastructure to enable automated functions such as data discovery, integration and access (Griffith & Truelove, 2021). Fig. 2-6 below illustrates the architecture of a federated spatial digital twin model.

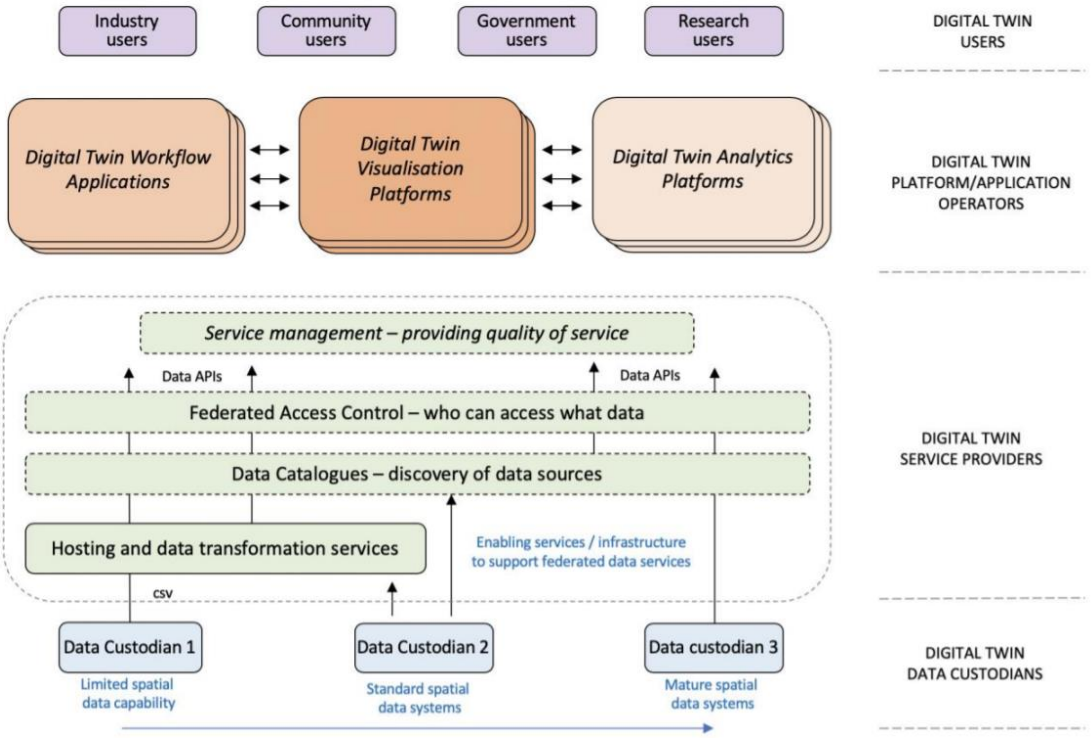


Fig. 2-6: Federated Spatial Digital Twin Functional Architecture. Source: Griffith & Truelove (2021).

Griffith & Truelove (2021) define three categories for digital twin platforms and applications: (a) visualization platforms, which are able to display data in both 3D and 4D; (b) analytics services, ranging from simple statistical processing tools to more complex modelling simulation and optimization systems using machine learning and agent-based modelling; (c) workflow applications extend analytic services with functions that allow end users to combine, select and interrogate data, usually along with visualization and analytic services. The authors believe there is a need to not only inform the community about the digital twin development, but also to provide opportunities for citizens to help identify and manage potential risks on a collaborative basis. The next section explores further the principles guiding the digital twinning process and their social aspects.

2.2 Principles for digital twin implementation and governance

As an effort to guide the development of digital twins for the built environment in the United Kingdom, the Centre for Digital Built Britain has launched the Gemini principles (Bolton et al., 2018). They are listed in Fig. 2-7, organized under the pillars of purpose, trust and function. These key values intend to enable a further connection of digital twins creating a National Digital Twin - NDT. The NDT will not be a huge singular model, but an ecosystem of digital twins connected via securely shared data, which requires an information management framework able to support federated architecture. And not even all digital twins would be connected, but only where this connection generates added value. As they can be connected in numerous ways, the ecosystem would consist different federations of digital twins, getting more diverse and interconnected over time.

Fig. 2-7: The Gemini Principles. Source: Centre for Digital Built Britain (2018).

Bolton et al. (2018) also recognize the variety within the ecosystem of digital twins and its impact on how they are implemented, classifying this diversity in the following aspects:

- *Variety of purposes*: (a) potential futures, such as strategic planning and simulation of proposed scenarios; (b) current state, like intervention management and real-time status monitoring and control; (c) record-keeping to enable learning from the past.
- *Variety of spatial scales*: (a) asset or building scale; (b) network or neighborhood scale; (c) system, city or regional scale; (d) national scale.

- *Variety of temporal scales*: (a) operational timescale; (b) reactive maintenance timescale; (c) planned maintenance timescale; (d) capital investment timescale.
- *Variety of approaches to modelling*: (a) geometric and geospatial modelling; (b) computational/mathematical/numerical modelling; (c) artificial intelligence and machine learning.

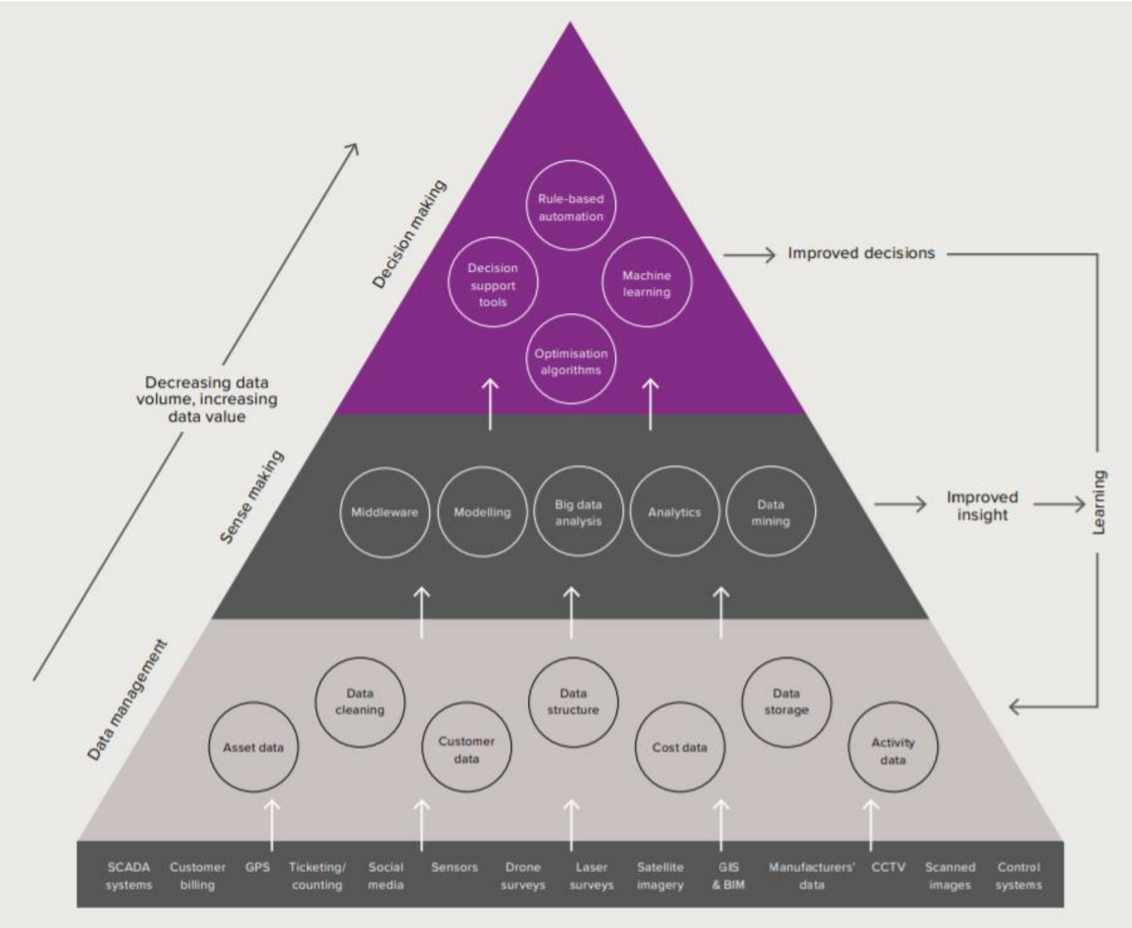


Fig. 2-8: The information value chain in a digital twin. Source: Centre for Digital Built Britain (2018).

According to Bolton et al. (2018), a digital twin must have a level of accuracy suited to its purpose in order to successfully add value to the users, as seen in Fig. 2-8. The extent to which it represents a physical reality depends on the quality of three essentials: the quality of the data on the virtually replicated asset; the adequacy of the algorithms, assumptions and code competence; the quality of visualization of the output. If compliant to the Gemini Principles, the NDT ecosystem would generate benefits to: (a) society, such as improved stakeholder engagement and higher-performing infrastructure; (b) economy, improving national productivity and measurement of outcomes; (c) business, like new markets, services, business models and entrants, by reducing uncertainty and improving risk management; (d) environment: less disruption and waste, once it enables the circular economy, with more reuse and greater resource efficiency.

According to Wan et al. (2019) , the development of a digital twin is progressive, requiring the technical apparatus and the social system responsible for its development, operation, and use to co-evolve. In the context of smart cities, digital twins are not context-free technologies that can be simply acquired and integrated into existing governance systems. For a meaningful digital twin application, insights and changes from a governance standpoint are crucial. The authors present then six propositions related to the city-level digital twin agenda, originating from an ongoing smart cities research project at the Cambridge Centre for Smart Infrastructure and Construction:

a) the creation of a digital twin is an ongoing process in which the technical system and the social system responsible for its development, operation, and use must co-evolve.
b) the progress in data science, particularly machine learning techniques, will complement existing urban and infrastructure theories, jointly contributing to the essential knowledge for digital twin development.
c) a city-level digital twin does not need to geometrically mirror the city; its spatial and temporal resolution should be dictated by its intended purpose.
d) in addressing complex policy challenges, a practical use of a digital twin involves identifying system-level risks and inefficiencies in development options and promoting cross-disciplinary collaboration, rather than solely relying on a singular model-based optimization.
e) the development of a digital twin's technical apparatus must integrate insights from a governance perspective to achieve the desired policy outcomes.

According to Woods & Freas (2019) “digital twins have an important role to play in understanding and managing the complex integration of multiple assets and systems that characterize community-scale projects”. The role of digital twins is to enable simulations and analysis that were previously impossible or uneconomic to perform. By analyzing some digital twin initiatives, the authors identified some key insights: accessing and managing data is the biggest challenge; an skilled and integrated team (even if from different organizations) is required to work collaboratively; the twin must support multiple stakeholders, such as residents and other end-users. It raises thus the question if governance models are ready to co-evolve with digital twins.

Aiming at embodying active citizenship into governance, Gleeson & Dyer (2017) evoke a new paradigm: collaborative urbanism, where citizens connect, communicate, collaborate, change and control the design, production and application of smart solutions. For them, cities are multi-layered entities and if these layers are properly aligned, a collaborative form of urban planning, governance and management arises. For them, the city is constituted of:

a) a physical layer: the urban infrastructure, the built environment and public spaces.
b) a meta layer: the data layer in the online world.
c) a control layer: real or virtual places where people make sense of data.

Pursuant to Wood (2015), the so-called *smart city* is the archetypal urban form of the data-driven society and, in order to serve human flourishing, they need to be detached from solely techno-economistic purposes and ground mostly in social ecological thinking. In the context of the smart city, Vassão (2017) considers *metadesign* as an accessible method to promote qualified and consequential creative work, where citizens are conscious and empowered on their role in urban planning. Based on a new social interaction repertoire, this approach takes advantage of digital interaction and mediates social change.

Kummitha & Crutzen (2017) undertook a comprehensive literature review on smart cities and identified that the academia approach the subject of smart cities in four different point of views: (a) restrictive, focused on ICT benefits; (b) reflective, which also focus on ICT benefits, but also consider human development as a by-product of technology advancement; (c) rationalistic, that considers technology as a by-product of human capital; (d) critical, which consider smart city initiatives as potentially harmful to citizens and communities. One of the challenges faced in urban planning, especially as we move towards using more complex technology, is that it is often top-down, focusing on technical infrastructure rather than citizen-centered approaches. Some obstacles to the culture of citizen engagement are (a) the polarization between top-down and bottom-up stakeholder groups, (b) the design of processes which are only intelligible to specialist groups and (c) the distrust in the value of collaboration.

The project Colouring London is one example of crowdsourcing project that leverages the potential of citizens to create valuable data regarding the building stock, the most important capital asset of a city and its most socio-economic resource with the greatest potential for energy reduction in cities (Alan Turing Institute, 2023). The project aims to fill the gap for an openly available dataset for UK buildings, making it easier to understand and forecast its dynamic behavior. This way, it tests a new type of open knowledge exchange platform designed to collate, capture, generate and drive the release of open building attribute data in an open platform code.

The base data is gathered from publicly available datasets, but the key feature of this initiative is the interface of the Colouring London platform for contributors. Fig. 2-9 below presents this interface, where citizens can collaboratively insert data regarding different aspects of the buildings, such as: location, current use, original use, construction date, size and shape, building materials, surrounding environment, builder and designer, performance, existence of environmentally friendly solution, site history, how the community sees that building. The data checking model is similar to other crowdsourcing platforms like OpenStreetMap and Wikipedia. In other words, as more volunteers contribute by adding data, the more accurate the data becomes and the more the model gets representative of reality.

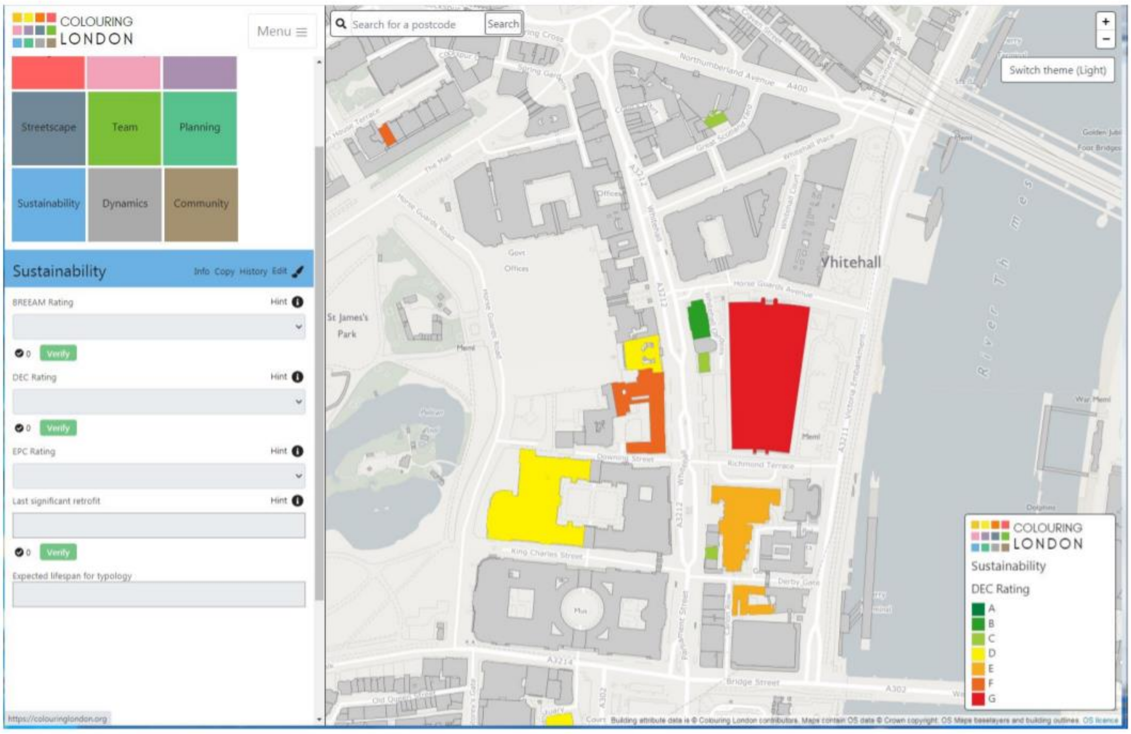


Fig. 2-9: The information value chain in a digital twin. Source: Centre for Digital Built Britain (2018).

Benach et al. (2017) demonstrated twelve grassroots initiatives in different countries, starting from the principle that meaningful change happens when the community is involved. The researchers perceive three different modes of participation: (a) done by vindicating social movements confronting certain situations or the current establishment; (b) pursued by citizens responding to a government invitation to participate in a debate designed by the administration (governance); (c) carried out by those who proactively assume the prominence of acting in an organized way to solve issues that affect them directly. By providing data not only to the government, but also to citizens, a citizen-centered digital twin enables more informed opinions on society.

One important argument to promote citizen engagement in the context of smart city projects is based on the great potential to connect and impact various aspects of urban life. These initiatives have a significant impact on communities, since the scale of some interventions brings more needs, advantages, and risks as a result than ever before.

In the context of smart city projects, citizen engagement has, for Smart Cities Information System (2020) a powerful role in: (a) understanding and addressing the needs and concerns of citizens; (b) empowering multi-level governance settings and increasing transparency in decision-making processes; (c) including a diversified group of people in the process, such as vulnerable citizens that would not participate in public hearings; (d) strengthening collaborative actions and bottom-up innovations; (e) building community trust and consensus and reaching a better sense of community ownership, what increases long-term success; (f) improve resource efficiency by exploring the perspectives and input of citizens as end-users and discovering creative solutions.

The Smart Cities Marketplace community hosted at the European Commission declared their commitment to create and foster accessible services for citizens contributing to sustainable cities and a livable environment. Their main objectives are translated in the following principles listed in the Manifesto for Citizen Engagement (European Commission, 2017):

a) It is decisive to raise citizen's awareness of the potential advantages and benefits of smart city projects, enhancing digital literacy at all levels and creating incentives and rewards for citizens and communities for their continuous engagement.
b) While designing smart cities solutions, it is important to reach out to underprivileged groups and city officials and urban experts should be trained to conduct meaningful and ethical engagement processes.
c) Existing collaborative models, such as cocreation, codesign and coproduction of solutions by citizens, must be further developed and adopted. Innovative ways must be explored to implement smart city projects in impoverished neighborhoods.
d) It is crucial to enhance procurement processes in a way that involves citizens in both specification and execution, while ensuring that elected public bodies retain ultimate responsibility for delivering essential services. Consolidating a framework with ongoing assessment and iteration based on citizen feedback is able to secure citizen engagement, which is essential to guaranteeing the continuity of a project regardless of political changes. When applying open government policies, it is important to also promote the use of open data by

citizens, developers and companies, engaging citizens in the evaluation of urban policies.

e) Privacy must be ensured by design. Trust is the backbone of smart city solutions and they must fully respect individual freedom and right to privacy. Data privacy regulations should be thoroughly developed, regularly updated and well-disseminated.

f) Quadruple helix cooperation and people-centered design must be promoted along with regional clusters linked to rural surroundings, building on entrepreneurship, replicable concepts and peer learning.

More than just a new governance model, migrating to quadruple helix also has the potential to boost the innovation process in smart city projects. The project +CityxChange, which aims to co-create energy-positive city blocks is embedded within what is called the Open Innovation 2.0 framework (Ahlers et al., 2019).

Table 2-2: How innovation modes evolved. Source: adapted from Markkula (2018).

Closed Innovation	Open Innovation	Open Innovation 2.0
Dependency	Independency	Interdependency
Subcontracting	Cross-licensing	Cross-fertilization
Solo	Bilateral	Ecosystem
Linear	Linear, leaking	Nonlinear mash-up
Linear subcontracts	Bilateral	Triple or quadruple helix
Planning	Validation, pilots	Experimentation
Control	Management	Orchestration
Win-lose game	Win-win game	Win more-win more
Box thinking	Out of the box	No boxes
Single entity	Single discipline	Interdisciplinary
Value chain	Value network	Value constellation

Table 2-2 below illustrates the evolution of innovation modes from closed innovation to open innovation 2.0, reflecting on new opportunities to include citizens in innovation ecosystems. This progression highlights a shift from dependency to interdependency, moving from solo efforts to ecosystem-based collaboration, and transitioning from linear processes to nonlinear mash-ups. The table also shows a change in focus from control and management to orchestration, fostering a "win more-win more" mentality over the traditional "win-lose" or "win-win" approaches. Furthermore, the evolution emphasizes the importance of interdisciplinary collaboration, moving from single-entity or discipline-focused initiatives to value constellations that involve diverse stakeholders and disciplines.

As illustrated in Fig. 2-10, some innovative methods of collaboration with citizens are proposed in the +CityxChange project, such as: (a) learning workshops composed by in-person discussion and site visits; (b) citizen observatories; (c) community-driven innovation tasks; (d) innovation playgrounds, where citizens, local companies and other stakeholders connect, ideate, develop and test urban prototypes and beta projects through crowd-solving, crowdfunding and match-funding (Ahlers et al., 2019).

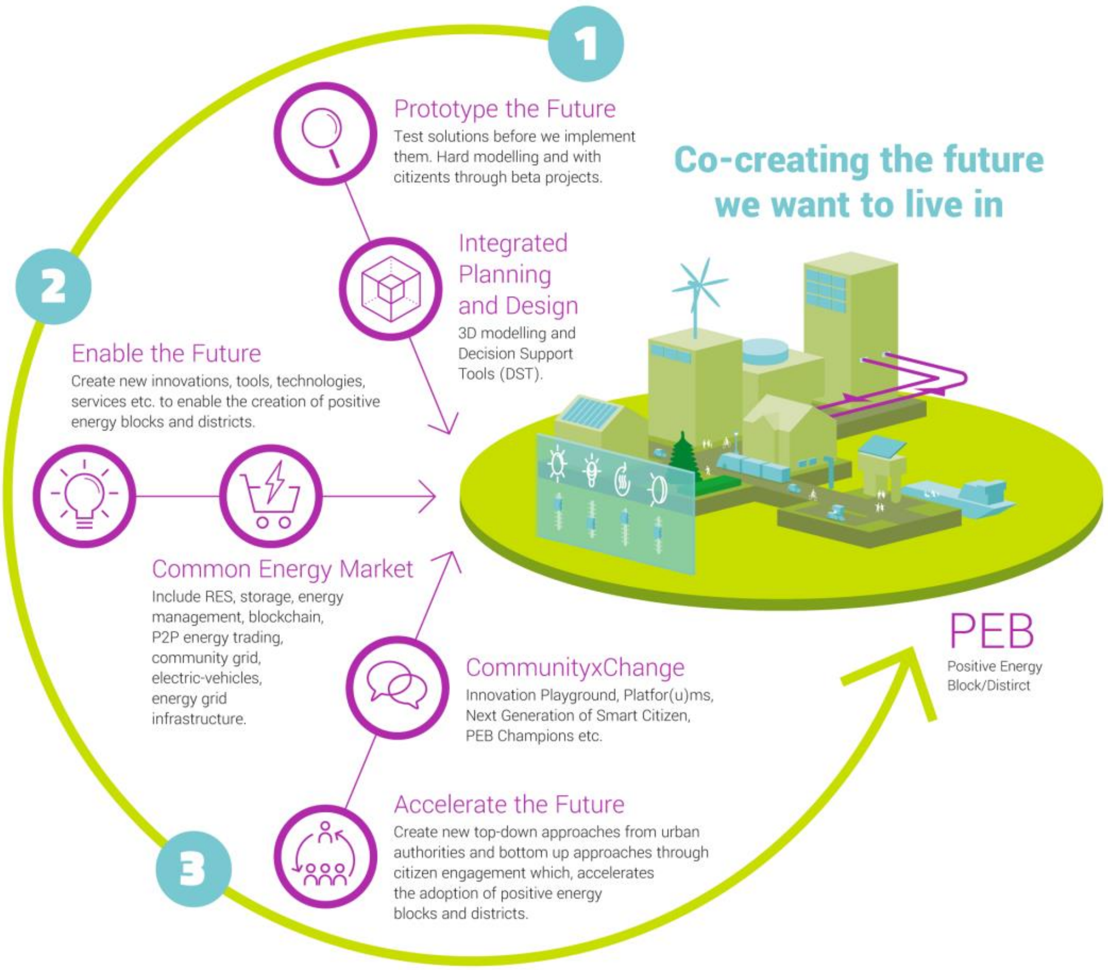


Fig. 2-10: Co-creation innovation framework. Source: Ahlers et al. (2019).

Another method for co-creation of urban futures is geodesign, a design framework that supports geographic information (Steinitz, 2014). Even though scale brings complexity, the term design is also applicable to the regional level in what is denominated “scenario-based studies of alternative futures”. Many authors have researched the potential of geodesign for collaborative processes, especially for enabling real-time visualization of proposed scenarios and advancing progressive stakeholders’ consensus, such as Slotterback et al. (2016), Eikelboom & Janssen (2017) and Haklay et al. (2018).

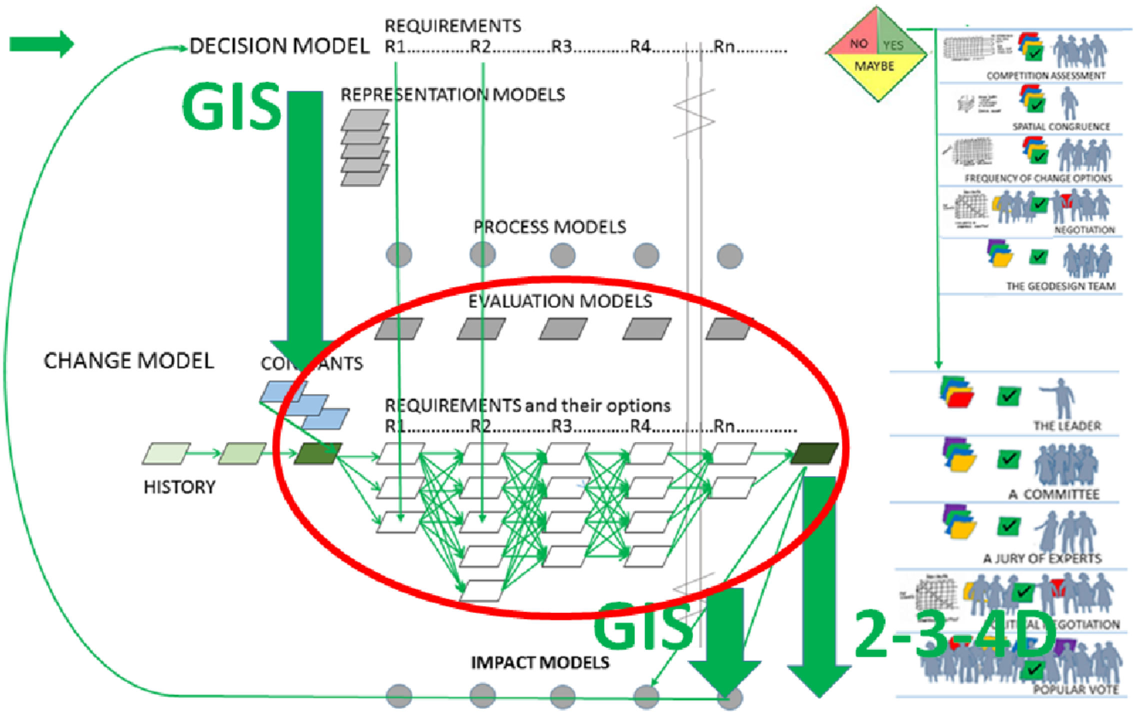


Fig. 2-11: Scope of the geodesign tool. Source: Ballal (2015).

Ballal (2015) developed a comprehensive geodesign platform, digitizing the steps and procedures of Steinitz methodology, which is already in practice for years and validated in workshops all across the world. For the author, digitizing is a natural progression of the framework and enables the collaboration of participants even if not physically together, scaling up the number of ideas and scenarios proposed and negotiated by the different stakeholders. Also, as it gets digital and online, it is easier to access existing geographic datasets and aim at decisions which are more consensual, but also grounded in data available to that territory. Fig. 2-11 presents a diagram with a geodesign workflow with its iterations and decision-making phases.

2.3 Conclusions

Instead of presenting cases, this literature review focused on introducing frameworks and also key insights that can be drawn from the integration between these frameworks. The physical representation of city elements and their integration into digital twins, as described by Batty (2018), directly feeds into the development of City Knowledge Models (Castelli et al., 2019), enabling precise modeling and evaluation of urban sub-systems. The flows of traffic and real-time dynamic data, corresponds to the "Data Collection" and "Modelling and Simulations" components of the UI paradigm (Castelli et al., 2019). The model of the low-frequency city simulating long-term urban growth and change (Batty, 2018), aligns with the "City Digital Twin and Decision-Making via Multidisciplinary Analysis and Optimization" component of the UI paradigm (Castelli et al., 2019).

More important than the name of the framework element is taking the specificity of digital twin applications into account while designing the structure of a digital twin. Bolton et al. (2018) explored further the diverse nature of digital twin ecosystems and their impact on implementation, categorizing the variety into four aspects: purposes, spatial scales, temporal scales, and modeling approaches.

Even amidst different types of digital twins, some organizations such as the Centre for Digital Built Britain have established general principles. The so-called Gemini Principles are divided into three categories: purpose, trust, and function. Purpose principles emphasize public good, value creation, and insight, ensuring digital twins contribute positively to society and provide valuable insights into the built environment. Trust principles focus on security, openness, and quality, ensuring transparency, data protection, and reliance on high-quality data. Function principles include federation, curation, and evolution, requiring a standard connected environment, clear ownership, governance, and the ability to adapt to evolving technology.

Woods & Freas (2019) emphasize the role of digital twins in understanding and managing complex community-scale projects. They identify key insights, including the challenge of data management, the need for skilled and integrated teams, and the importance of supporting multiple stakeholders. This raises a question about the readiness of governance models to co-evolve with digital twins. Gleeson & Dyer (2017) propose a collaborative urbanism paradigm, focusing on active citizenship and multi-layered cities. Wood (2015) suggests that smart cities should prioritize social ecological thinking over techno-economistic purposes. Vassão (2017) promotes *metadesign* as an approach to empower citizens in urban planning. One of the methods for co-creating urban and regional futures is *geodesign*, a design framework based on geographic information (Steinitz, 2014).

The Manifesto for Citizen Engagement (European Commission, 2017) highlights key principles, such as raising awareness, ensuring inclusivity, promoting collaboration, improving procurement mechanisms, applying open government policies, ensuring privacy, and fostering quadruple helix cooperation. Finally, while creating new solutions to daily life problems in cities, technology must not have an end in itself, but always remain a means at the service of citizens. On the other hand, technology can also be seen as an opportunity to upscale, strengthen and disseminate existing collaboration methods, empowering the civil society by including more citizens in decision-making processes.

We can conclude that a shift from top-down approaches to more citizen-centered and decentralized governance strategies, such as federated data models, can lead to more successful implementation of digital twins. Emphasizing collaboration and active citizenship can help create more inclusive, adaptable urban environments that make use of the full potential of digital twins and related technologies.

Through an in-depth exploration of digital twin frameworks, this literature review lays the foundation for a global assessment of digital twins, which will be detailed in the subsequent chapter. By examining the current state of digital twin technology and its various capabilities, the review sets the stage for a more extensive analysis.

2.4 References

Ahlers, D., Driscoll, P., Wibe, H., & Wyckmans, A. (2019). Co-Creation of Positive Energy Blocks. *IOP Conference Series: Earth and Environmental Science*, *352*(1). https://doi.org/10.1088/1755-1315/352/1/012060

Alan Turing Institute. (2023, April 9). *Colouring London*. Https://Colouringlondon.Org/.

Ballal, H. (2015). *Collaborative planning with digital design synthesis* [UCL (University College London)]. https://discovery.ucl.ac.uk/id/eprint/1471177/

Batty, M. (2018). Digital Twins Introduction. *Environment and Planning B: Urban Analytics and City Science*, *45*(5).

Batty, M. (2020, February 4). *Digital Twins, Triplets & The Rest*. http://www.spatialcomplexity.info/files/2020/02/Digital-Twins-COLUMBIA.pdf

Benach, N., Alió, M. À., Aco, B., & Rojas, C. J. (2017). *Participación Ciudadana en los Procesos de Hacer Ciudad*. http://www.ub.edu/geocrit/participacion-ciudadana-social.pdf

Bolton, A., Enzer, M., Schooling, J., Butler, L., Dabson, I., & Evans, M. (2018). The Gemini Principles: Guiding values for the national digital twin and information management framework. *Centre for Digital Built Britain: University of Cambridge*.

Castelli, G., Tognola, G., Campana, E. F., Cesta, A., Diez, M., Padula, M., Ravazzani, P., Rinaldi, G., Savazzi, S., Spagnuolo, M., & Strambini, L. (2019). Urban Intelligence: A Modular, Fully Integrated, and Evolving Model for Cities Digital Twinning. *HONET-ICT 2019 - IEEE 16th International Conference on Smart Cities: Improving Quality of Life Using ICT, IoT and AI*. https://doi.org/10.1109/HONET.2019.8907962

Centre for Data Leadership. (2020). *Data Leadership Guidance Note*. https://www.smartcitiescouncil.com/sites/default/files/anz_smartcitiescouncil_com/public_resources/guidance_note_digital_twin_issue_0.pdf

Eikelboom, T., & Janssen, R. (2017). Collaborative use of geodesign tools to support decision-making on adaptation to climate change. *Mitigation and Adaptation Strategies for Global Change*, *22*(2). https://doi.org/10.1007/s11027-015-9633-4

European Commission. (2017). *Inclusive Smart Cities: A European Manifesto on Citizen Engagement*. Https://Smart-Cities-Marketplace.Ec.Europa.Eu/Sites/Default/Files/EIP-SCC%20Manifesto%20on%20Citizen%20Engagement%20%26%20Inclusive%20Smart%20Cities.Pdf.

Gleeson, D., & Dyer, M. (2017). Manifesto for collaborative urbanism. In *Springer Tracts in Civil Engineering*. https://doi.org/10.1007/978-3-319-47904-0_1

Griffith, C., & Truelove, M. (2021). *Framework for Spatially Enabled Digital Twins: Information Paper*. https://www.anzlic.gov.au/sites/default/files/files/Data61%20Digital%20Twin%20Framework%20Information%20Paper%20-%20February%202021.pdf

Haklay, M., Jankowski, P., & Zwoliński, Z. (2018). Selected modern methods and tools for public participation in urban planning - A review. *Quaestiones Geographicae*, *37*(3). https://doi.org/10.2478/quageo-2018-0030

Kummitha, R. K. R., & Crutzen, N. (2017). How do we understand smart cities? An evolutionary perspective. *Cities*, *67*. https://doi.org/10.1016/j.cities.2017.04.010

Markkula, M. (2018). Open innovation 2.0 the new mode of digital innovation for prosperity and sustainability. In *Innovation, Technology and Knowledge Management*.

Meta, I., Serra-Burriel, F., Carrasco-Jiménez, J. C., Cucchietti, F. M., Diví-Cuesta, C., García Calatrava, C., García, D., Graells-Garrido, E., Navarro, G., Làzaro, Q., Reyes, P., Navarro-Mateu, D., Gil Julian, A., & Eguskiza Martínez, I. (2021). The Camp Nou Stadium as a Testbed for City Physiology: A Modular Framework for Urban Digital Twins. *Complexity*, *2021*. https://doi.org/10.1155/2021/9731180

Raes, L., Michiels, P., Adolphi, T., Tampere, C., Dalianis, A., McAleer, S., & Kogut, P. (2022). DUET: A Framework for Building Interoperable and Trusted Digital Twins of Smart Cities. *IEEE Internet Computing*, *26*(3). https://doi.org/10.1109/MIC.2021.3060962

Slotterback, C. S., Runck, B., Pitt, D. G., Kne, L., Jordan, N. R., Mulla, D. J., Zerger, C., & Reichenbach, M. (2016). Collaborative Geodesign to advance multifunctional landscapes. *Landscape and Urban Planning*, *156*. https://doi.org/10.1016/j.landurbplan.2016.05.011

Smart Cities Information System. (2020). *Citizen Engagement Solution Booklet*. https://smart-cities-marketplace.ec.europa.eu/insights/solutions/solution-booklet-citizen-engagement

Steinitz, C. A. (2014). A Framework for geodesign. *ESRI Press*.

Vassão, C. A. (2017). Design and Politics: Metadesign for social change. *Strategic Design Research Journal*, *10*(2). https://doi.org/10.4013/sdrj.2017.102.07

Wan, L., Nochta, T., & Schooling, J. M. (2019). Developing a city-level digital twin - Propositions and a case study. *International Conference on Smart Infrastructure and Construction 2019, ICSIC 2019: Driving Data-Informed Decision-Making*. https://doi.org/10.1680/icsic.64669.187

Wood, D. M. (2015). Smart City, Surveillance City. *Computers and Law*, *26*(2).

Woods, E., & Freas, B. (2019). *Creating Zero Carbon Communities: The Role of Digital Twins*. Https://Www.Iesve.Com/Discoveries/Whitepaper/5938/Navigant-Role-of-Digital-Twins.

3 Global Assessment of Digital Twins

3.1 Introduction

The rapid pace of urbanization and the pressing need for sustainable development have led to the emergence of innovative technological solutions to address complex urban challenges. One such breakthrough is the application of the concept of digital twins into the spatial context, which has gained significant traction in recent years. This chapter presents global assessment of digital twins, providing a comprehensive understanding of their role in enhancing urban management, planning, and overall quality of life.

In order to set the foundation for the research, it is important to establish the definition of digital twin and which of them are included in the scope of this assessment. In some cases the initiative is named as a "digital twin", in other cases similar terms are used such as "city model", "3D geoportal" or "urban data platform". Fig. 3-11 below illustrates the scale of selected digital twins within the scope of this research. This inventory includes the virtual representations of:

a) *Physical objects or environments* (natural or man-made) in different scales, going from large infrastructure (entire highways, ports and airports) to regions and countries. It excludes thus models of buildings, bridges and other single pieces of infrastructure (much more numerous). On the other hand it excludes also the planet-wide digital twins, specially used for detailed climatic simulations. The reason for this is to select a range of digital twins with certain similarity of stakeholders context and technical complexity.
b) *Processes or systems* directing impacting the physical environment at the district, such as water flow and electricity load at an urban scale or complex social and economic models.

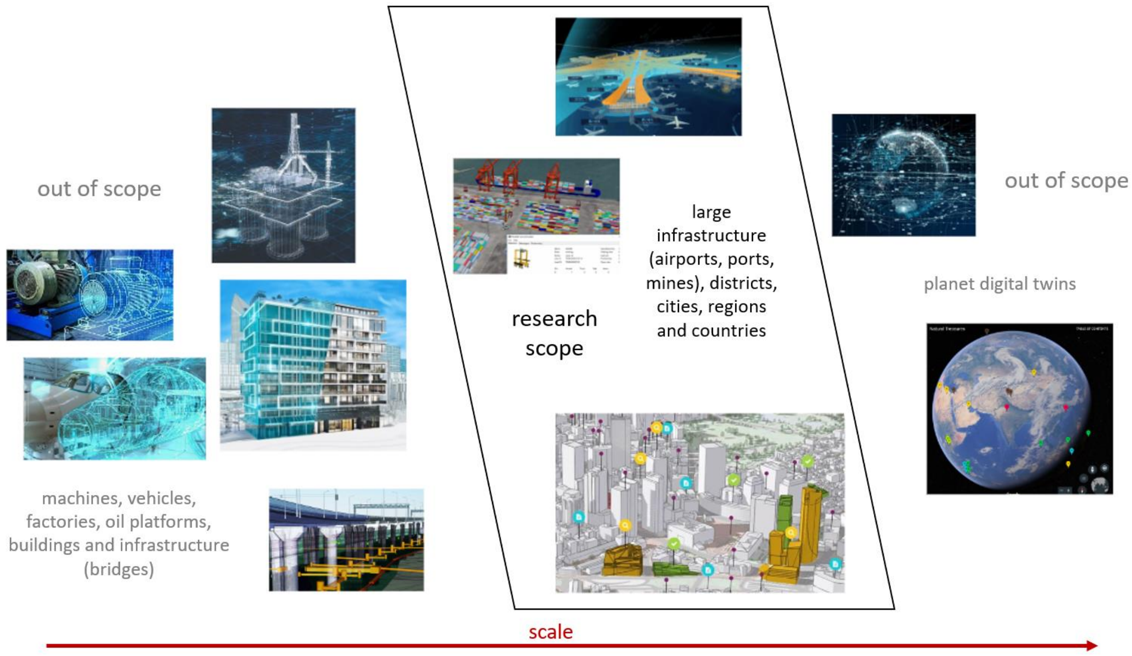


Fig. 3-1: Digital twins within research scope.

As urban areas grapple with the challenges of increasing populations, infrastructure demands, and environmental concerns, digital twins emerge as a powerful tool for promoting efficiency and sustainability. This chapter also investigates the multifaceted applications of digital twins in use cases such as city planning and management, highlighting their potential to optimize resource allocation, support data-driven decision-making, and foster smart city initiatives.

3.2 Assessment

Given the transformative potential of digital twins, a global assessment becomes crucial to identify best practices, promote knowledge sharing, and enhance the adoption of this technology in cities and regions worldwide. This part of the chapter outlines the *rationale* behind the assessment.

The data collection regarding digital twins took place from December 2020 to March 2023. The search on academic publications resulted in very few results, making it necessary to go for other sources. They were identified through periodic and extensive research based on the use of keywords in different languages on search engines, newsletters, specialized websites, academic papers, white papers, company websites and reports of international organizations. All initiatives were assessed on multiple attributes presented on Table 3-1, chosen based on the their relevance, applicability among different typologies of digital twins and assessment feasibility.

Table 3-1: Assessed attributes of digital twins.

Attributes	Classification	Explanation
Name	n/a	The title that best leads to online information to the initiative.
Place	n/a	The location of the initiative.
Country	n/a	The country of the initiative.
Scale	Infrastructure, District, City or Region	Kind/extension of area virtually twinned. "Infrastructure" encompasses ports, airports, highways and utility systems. "District" applies to university campus and neighborhoods, while "City" to entire municipalities and "Region" to countries or provinces. The scale of the digital twin leads to specific challenges and use cases.
Ownership	Public, Private, Academia, Unsure	Even if developed by a third party, this attribute relates to who actually owns the model and the data, so who gave the assignment for development.
Technology Maturity Level	1, 2, 3, 4 and 5	This maturity level classification is adapted from building digital twins (Atkins, 2019) and measures if the digital twin is capable of making use of more or less advanced technologies.
Implementation Maturity Level	Strategy, Experimental, Insightful, Intelligent	This maturity level classification was developed by the European research project DUET (DUET, 2022b) and measures the actual outcomes and level of implementation of the digital twins.

Accessible	Partial, Internal, Public, Unsure	Does the digital twin have a publicly accessible interface or a dedicated website?
Open Data	Open Data, Not Open Data, Unsure	Is the data visible in the digital twin publicly available for download?
Open Source	Open Source, Not Open Source, Unsure	Is the digital twin code accessible in portals such as GitHub or available on-demand?
Continuity	Continuous, One-time Model, Unsure	Continuous project that the ones part of an on-going initiative, while discontinuous are digital twins developed as one-time models for specific purposes, such as research.
3D-enabled	3D, 2D, Unsure	Does the digital twin offer 3D visualization?
Operator	n/a	If private, the company responsible for most of the development and maintenance of the digital twin software application.
Main Use Cases	n/a	For which purpose was the digital twin designed for, or how has it been used?
Website	n/a	Link to the dedicated website to the digital twin.
References	n/a	Link to online references about the digital twin with more information, such as news articles or government websites.

As mentioned in the grey rows of Table 3-1, the digital twins were assessed by two different perspectives concerning their maturity level in order to encompass both the technology aspect and the implementation aspect. Atkins (2019) developed a classification to assess the maturity of digital twins of buildings, so some adjustments were made to adapt it to the context of more spatially-extensive digital twins (especially districts, cities and regions), where Building Information Modelling - BIM is not as important. Table 3-2 below proposes the different maturity levels according to this adapted framework.

Table 3-2: Technology Maturity Level of Digital Twins, adapted from Atkins (2019).

Level	Defining Principle	Technologies and Characteristics
0	Reality capture	Point-clouds, photogrammetry, undifferentiated 3D mesh
1	Dataset	Semantic 2D or 3D dataset
2	Application	Application with dedicated interface enabling queries and simulations
3	Real-time	Model is enriched with real-time data includes data extracted on real-time from sensors
4	Two-way	Two-way data integration, enabling remote and immersive operations, control the physical from the digital
5	Autonomous	Complete self-governance over operations and maintenance with total oversight and transparency

DUET (Digital Urban European Twins) is a European innovation initiative involving different partners from across Europe which leverages the advanced capabilities of digital twins, to help public sector decision-making become more democratic and effective (DUET, 2022a). In this initiative, another maturity level was developed, focusing specially on the outcomes and implementation level of the digital twin. The way the four categories were used in the context of this assessment is further explained below:

a) *Strategy*: it means there is a political/organization decision to develop a digital twin. It can be a public speech, publication of guidelines, a formal act or setting up a team to work on the topic.
b) *Exploratory*: there is already a working application used for visualization or simulations, but the digital twin aspect is still being tested.
c) *Insightful*: the application is already generating important insights for the organization and is already incorporated to internal work processes.
d) *Future-ready*: the digital twin makes uses of multiple datasets and is able to generate real time insight powered by artificial intelligence models.

3.3 General Findings

This section will present the results on each of the attributes presented on Table 3-1 above. This assessment of digital twins identified 334 initiatives from 58 countries. Some locations are partially or integrally twinned in different independent initiatives, such as Singapore (6 initiatives), Beijing (5 initiatives), São Paulo, New York, Tokyo and Shenzen (4 initiatives) and Rio de Janeiro, Dublin, Shanghai, Orlando and the Netherlands (3 initiatives). Fig. 3-2 shows the 12 countries with more digital twin initiatives identified.

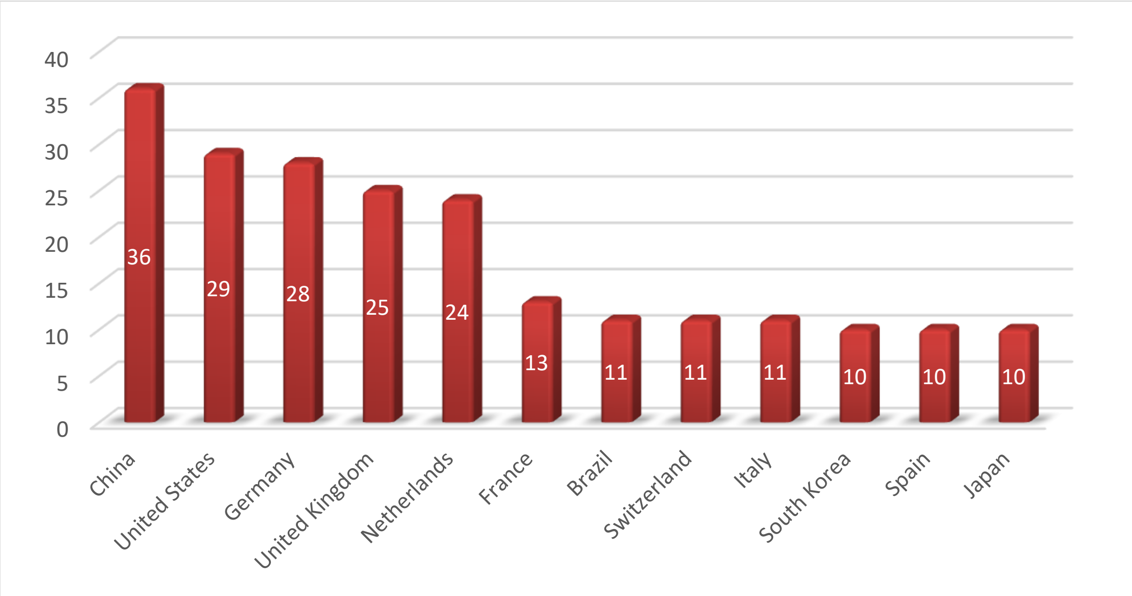


Fig. 3-2: Countries in number of digital twin initiatives.

3.3.1 Region

Fig. 3-3 presents an overview of the distribution of digital twins across various regions worldwide. Europe dominates the digital twin landscape, boasting a total of 173 digital twins, which constitutes a significant 52% share of the assessed initiatives. Asia follows suit as the second-largest region for digital twins, with 72 instances making up 22% of the total share. North America holds the third spot, possessing 35 digital twins, which accounts for a modest 10% share. Latin America comes in fourth with 23 digital twins, contributing to 7% of the global share. Meanwhile, both the Middle East and Oceania share similar numbers, each having

14 digital twins and representing 4% of the market share. Lastly, Africa trails behind with only 3 digital twins, occupying a minimal 1% share in the worldwide landscape of digital twins.

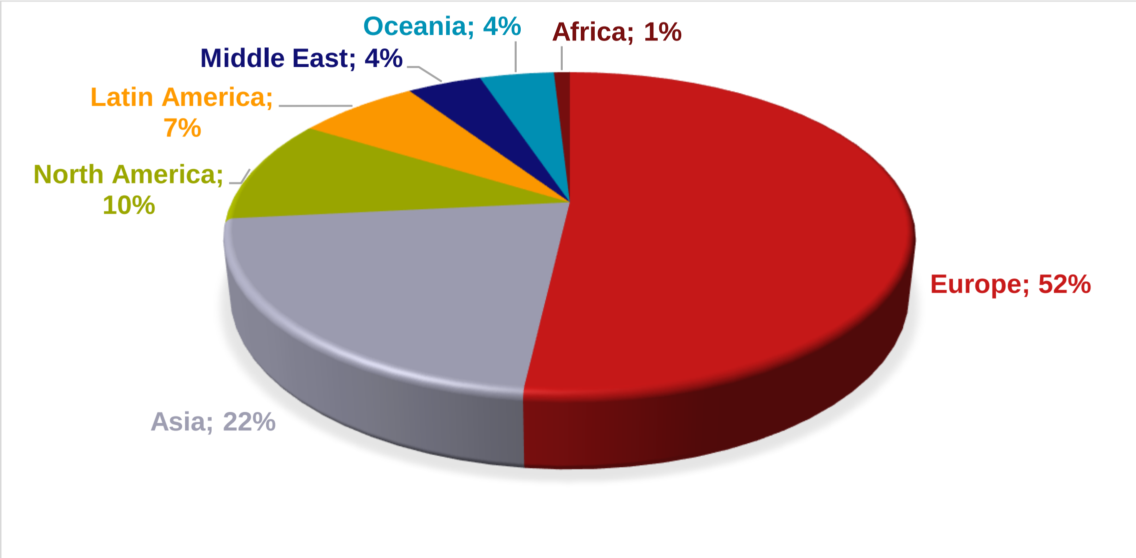


Fig. 3-3: Digital twin initiatives per world region.

Fig. 3-4: Global distribution of the 334 assessed digital twin initiatives.

3.3.2 Scale

Fig. 3-5 below elucidates the distribution of digital twins based on the scale of implementation. The majority of digital twins are deployed at the city level, with 184 instances representing a commanding 55% share of the total market. The district scale comes in at a distant second, featuring 65 digital twins and accounting for 19% of the global share. When it comes to infrastructure (mining, airports, ports and highways), there are 45 digital twins implemented, which constitute a 13% share in the overall landscape. Lastly, digital twins utilized at the regional level account for the smallest portion of the market, with 40 instances making up 12% of the total share. This data highlights the varied application of digital twins across different scales, with a clear majority in city-level deployment.

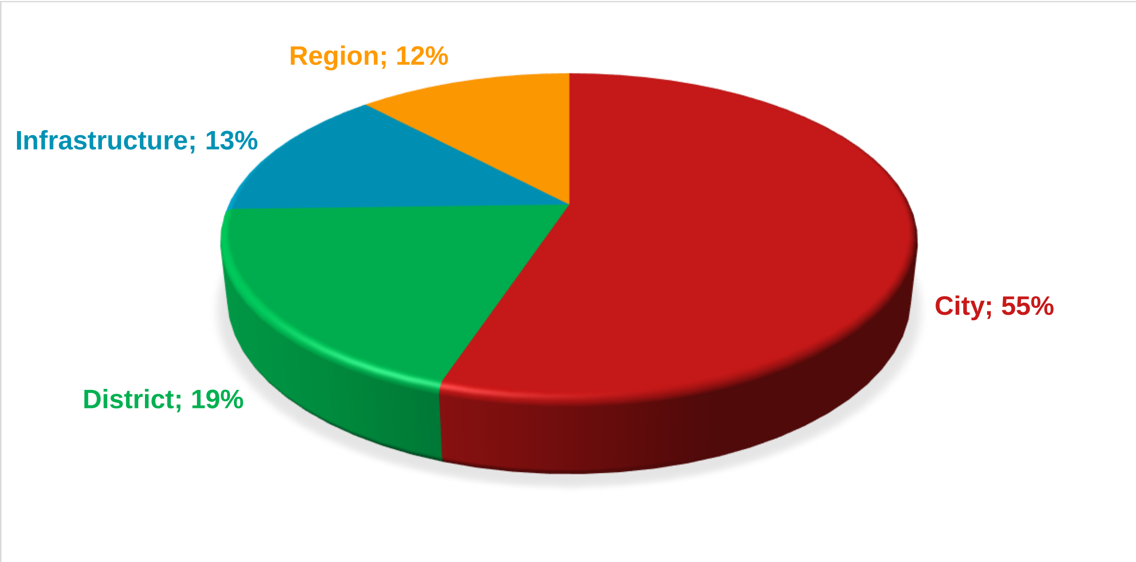


Fig. 3-5: Digital twin initiatives per scale.

3.3.3 Ownership

Fig. 3-6 below provides a breakdown of digital twin ownership, revealing a clear preference for public ownership. With 229 instances, public ownership accounts for a substantial 69% of the total share. Private ownership follows, representing 24% of the market with 80 digital twins. Academia holds a smaller portion of the ownership landscape, contributing 23 digital twins, which equates to 7% of the overall share. Lastly, there are two instances where the ownership is uncertain, making up a negligible 1% of the total. The data underscores the dominance of public ownership in the realm of digital twins, while also illustrating the involvement of private and academic entities.

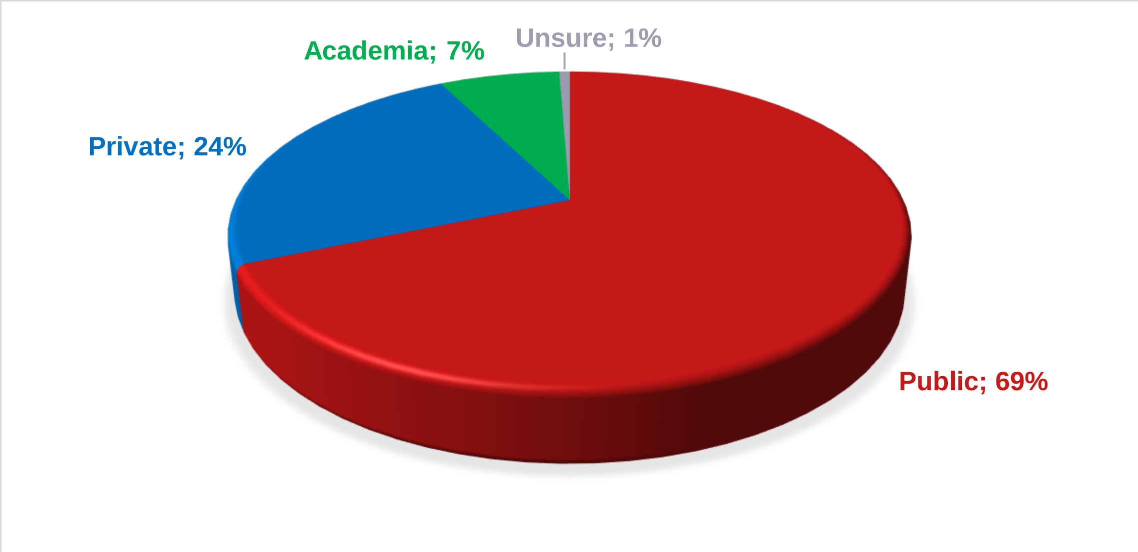


Fig. 3-6: Digital twin initiatives per ownership.

3.3.4 Accessibility and Openness

Fig. 3-7 outlines the accessibility levels of digital twins, providing insight into the extent to which they are made available for different user groups. Digital twins with internal accessibility are the most common, with 166 instances accounting for 50% of the total share. This indicates that half of the digital twins are accessible exclusively to authorized personnel or organizations. Public accessibility comes in second place, as 118 digital twins, or 35%, are available to the general public. Instances with uncertain accessibility make up 12% of the total, represented by 41 digital twins. Finally, a minor portion of digital twins, totaling 9 instances, offers partial accessibility, which constitutes a mere 3% share. The data showcases the varying degrees of accessibility in digital twin implementations, with a notable restriction for internal access.

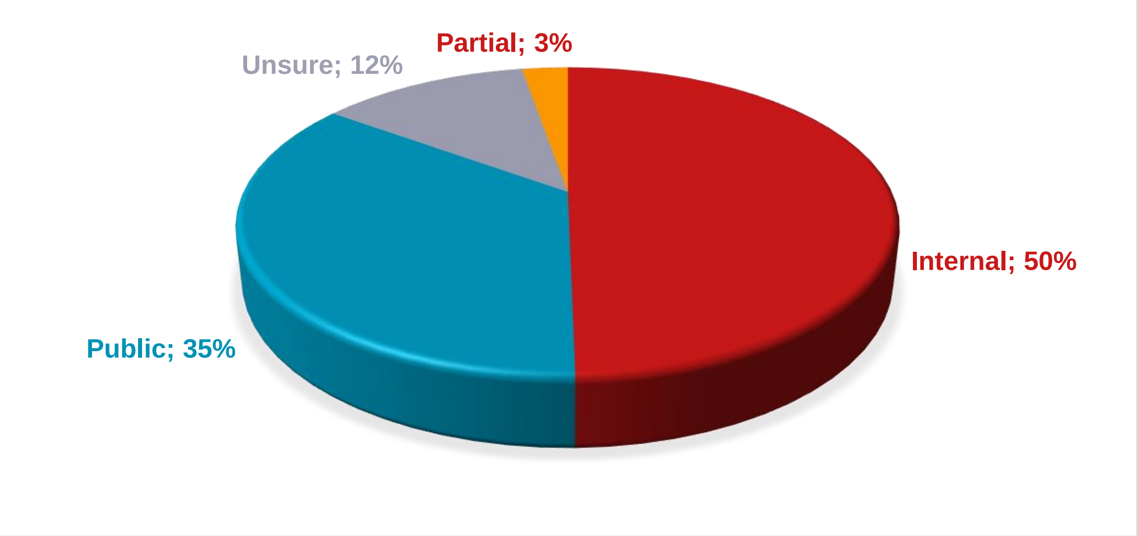


Fig. 3-7: Digital twin initiatives per accessibility.

Fig. 3-8 sheds light on the data openness in the digital twin landscape. A significant number of digital twins, amounting to 164 instances, do not provide open data, constituting 49% of the total share. In contrast, 93 digital twins, or 28% of the market share, do provide open data, enabling users to access, download and utilize most of the information. In a considerable number of cases, the open data status remains uncertain. Specifically, 77 instances, or 23% of the total share, fall under the 'unsure' category. The data highlights a prevailing tendency to not utilize open data policies in digital twin implementations, while also showcasing instances where open data is being incorporated and instances with ambiguous open data status.

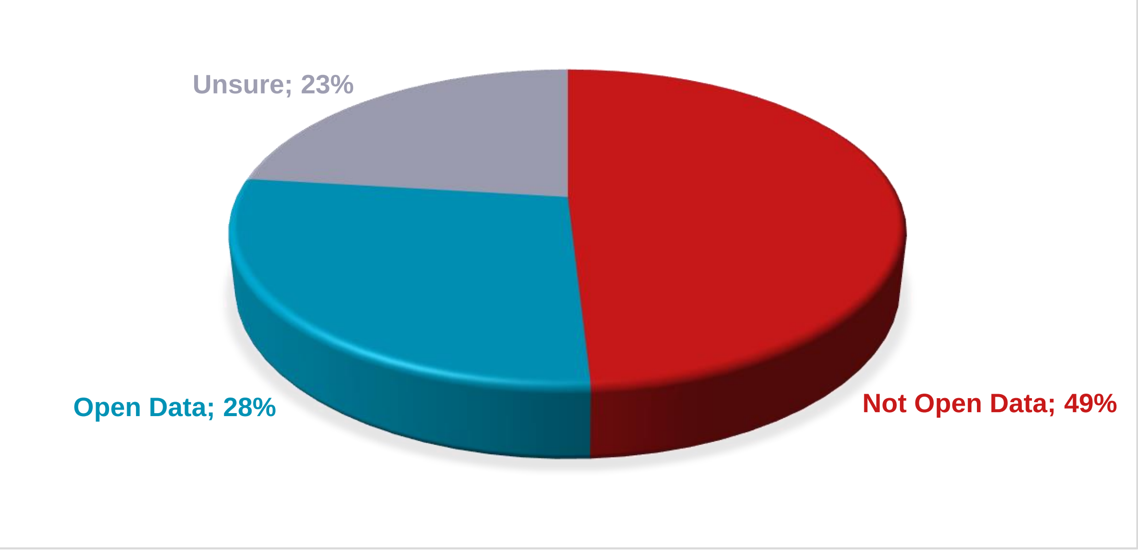


Fig. 3-8: Share of open data digital twin initiatives.

Fig. 3-9 presents an overview of publicity of code in the digital twin domain. A vast majority of digital twins, totaling 248 instances, are not open-source, making up a substantial 74% of the initiatives. This suggests that proprietary solutions are utilized in most digital twin implementations. For 73 instances, or 22% of the total share, the use of open-source technology is uncertain. These digital twins may employ a mix of proprietary and open-source solutions, or their technology stack may not be disclosed. In contrast, only a small fraction of digital twins, amounting to 13 instances, or 4% of the market share, employ open-source technology providing access to their code. The data highlights a strong inclination towards non-open-source solutions in the digital twin landscape, with limited open-source initiatives.

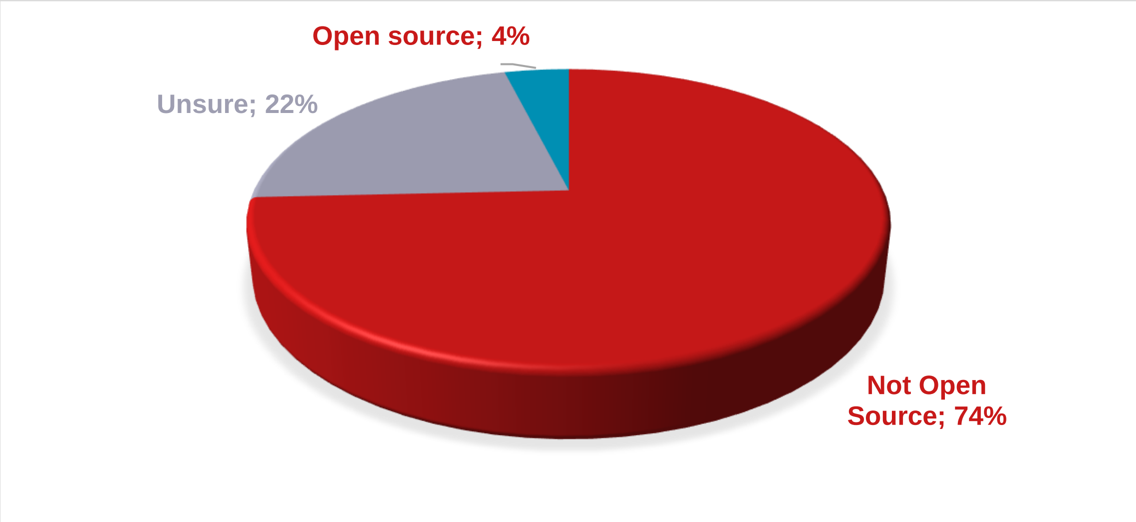


Fig. 3-9: Share of open source digital twin initiatives.

3.3.5 Continuity

Fig. 3-10 below provides an insightful analysis of the continuity of digital twin projects. A significant number of digital twins, 166 instances, are part of continuous projects, accounting for 50% of the total share. This indicates that half of the digital twin implementations are maintained and updated on an ongoing basis. In many cases, the continuity of the projects remains uncertain, as seen in 128 instances, which make up 38% of the overall share. Finally, 40 digital twins, or 12% of the market share, are not part of continuous projects, suggesting that these implementations were developed as a one-time model for research or specific analysis.

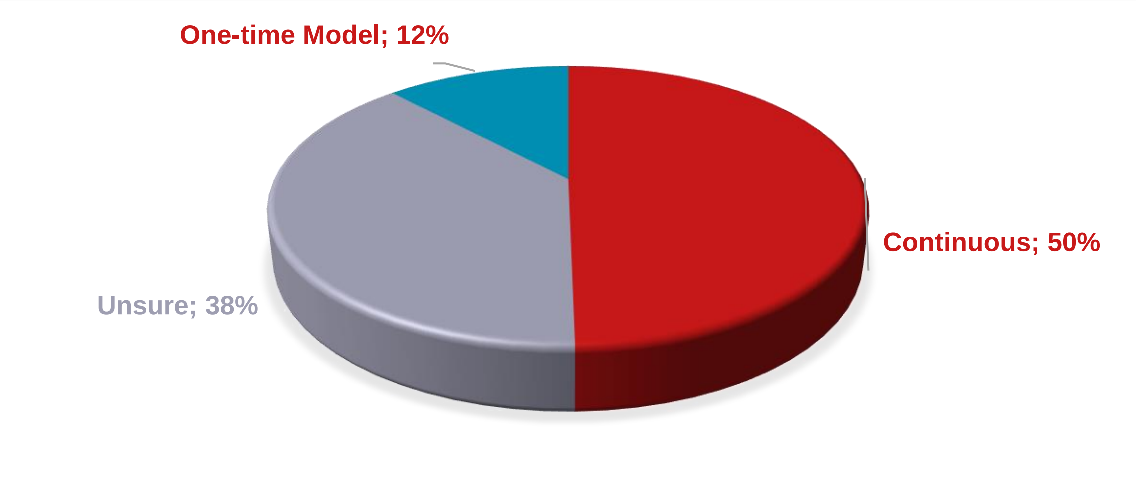


Fig. 3-10: Share of continuous digital twin initiatives.

3.3.6 3D-Enabled

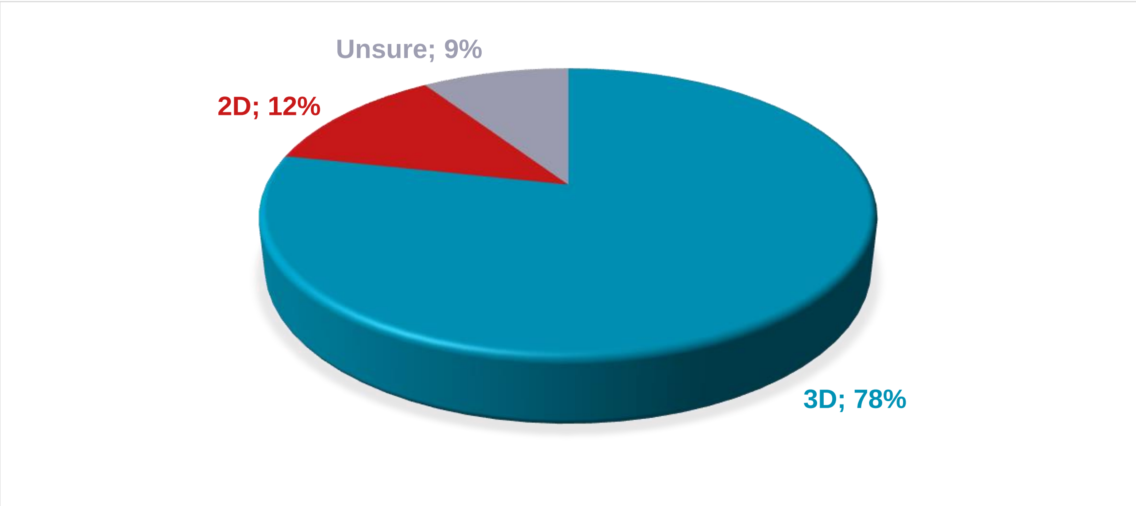


Fig. 3-11: Share of 3D-enabled digital twins.

Fig. 3-11 above presents a clear picture of the prevalence of 3D-enabled digital twins. As expected, a considerable majority of digital twins, amounting to 262 instances, incorporate 3D visualization, thus 78% of the total share. This suggests that 3D visualization is a crucial aspect of most digital twin projects. In contrast, 41 digital twins, or 12% of the total share rely on alternative visualization techniques or focus on non-visual aspects of digital twins. For 31 instances, or 9% of the total share, the use of 3D technology is uncertain, since their visualization methods are undisclosed.

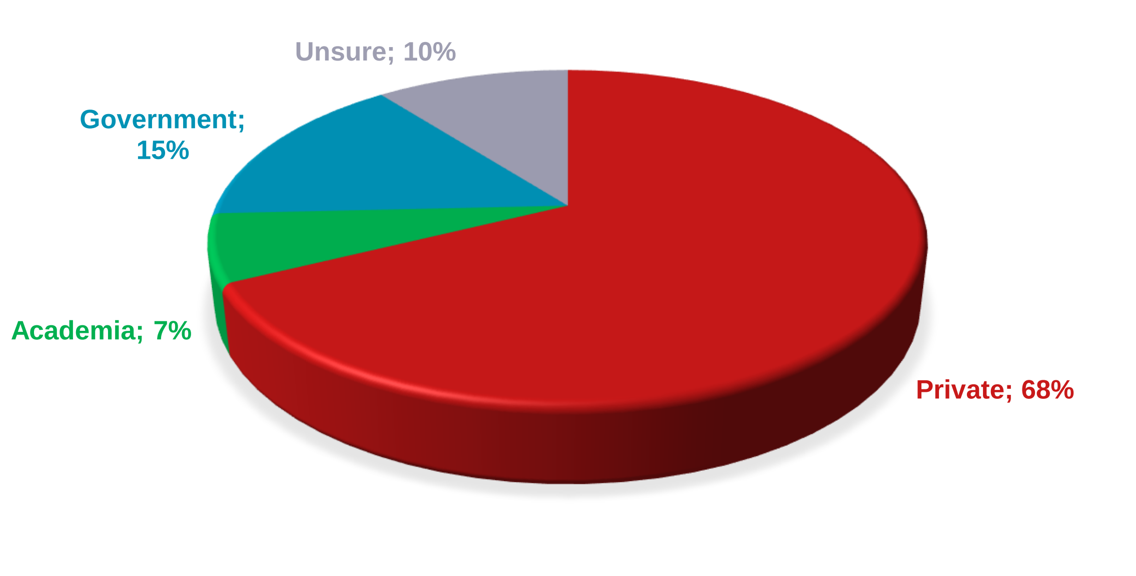


Fig. 3-12: Digital twins per type of operator.

3.3.7 Operators

Fig. 3-13 provides a valuable overview of the distribution of digital twin operators across different sectors, revealing the prominence of private, government, and academic entities in the field. With private operators making up a significant 68% (226 instances) of the total share, it is evident that private organizations play a vital role in the operation and development of digital twin projects. This indicates a strong interest and investment from the private sector in digital twin technology.

Government operators, however, also play a substantial role, holding the second-largest share of 15% (51 instances) in digital twin operations. This showcases the engagement of public organizations in leveraging digital twins for various urban planning and management applications, as well as their commitment to facilitating innovation in the sector. Meanwhile, academic institutions contribute to a smaller but still noteworthy extent, operating 22 digital twins and constituting 7% of the overall share. This involvement highlights academia's role in researching and advancing digital twin technology, as well as fostering collaboration with other sectors.

Lastly, the operator sector remains undetermined in 35 instances, accounting for 10% of the total share. This could point to a mix of operators or perhaps nascent projects still in the process of identifying their primary operators.

Overall, the data underscores the leading role of private operators in the digital twin domain, while also accentuating the crucial contributions of government and academic institutions in driving the development and adoption of digital twin technology.

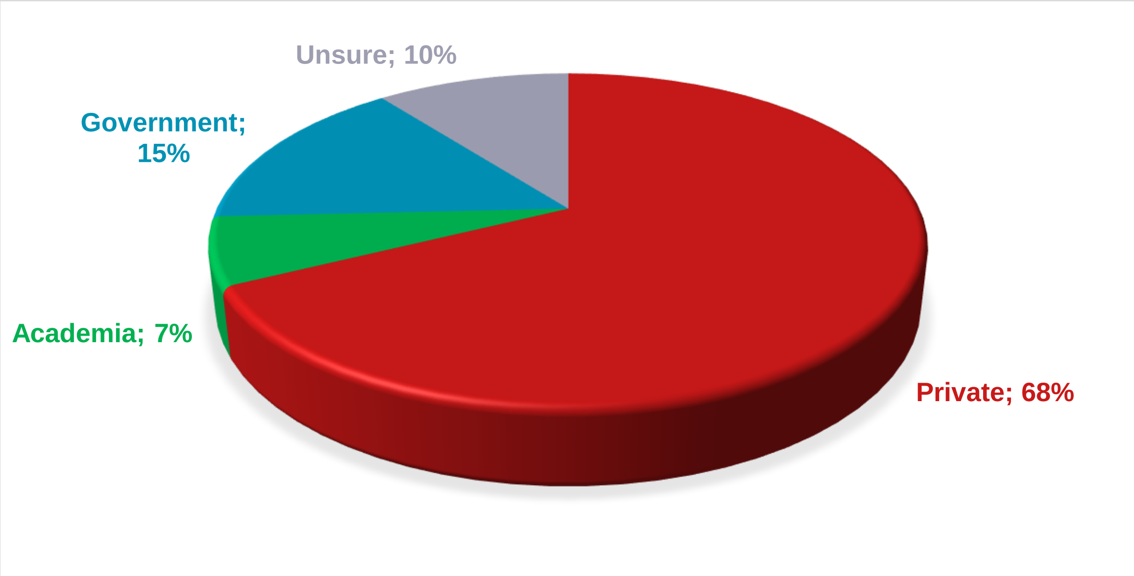


Fig. 3-13: Digital twins per type of operator.

While Fig. 3-14 presents the highest ranking companies among the assessed digital twin initiatives operated by a private organization, Fig. 3-15 illustrates their market share. Almost half (49%) of the initiatives are operated by other 83 companies, what shows that the market is still predominantly dominated by local smaller companies. The list below showcases the most prominent digital twin operators along with the countries where their headquarters are located. These operators offer innovative solutions and services in the spatial digital twin industry.

a) ESRI (United States): A global leader in geographic information system (GIS) software, offering digital twin solutions that integrate geospatial data and analytics for smarter decision-making (ESRI, 2023).
b) VCSystems (Germany): A technology company specializing in the development of digital twins for urban planning, infrastructure, and asset management (VCSystems, 2023).
c) VU.CITY (United Kingdom): A provider of interactive and precise 3D city models, enabling data-driven decision-making in urban planning and development (VU.City, 2023).

d) 51World (China): A leading innovator in the creation of virtual digital twin environments, focusing on smart cities, autonomous vehicles, and aviation (51World, 2023).
e) Bentley (United States): A renowned software company offering advanced digital twin solutions for infrastructure projects, asset performance, and construction management (Bentley, 2023).
f) CityZenith (United States): A smart city software company providing a powerful digital twin platform to visualize, analyze, and optimize urban environments (Cityzenith, 2023).
g) Dassault Systemes (France): A global leader in 3D design, engineering, and digital twin solutions for various industries, including aerospace, automotive, and construction (Dassault Sistèmes, 2023).
h) Simplex Mapping (Israel): A provider of digital twin services for urban planning, transportation, and infrastructure management (Simplex Mapping, 2023).
i) Geodan (Netherlands): A geospatial company specializing in location intelligence, offering digital twin solutions for smart cities, infrastructure, and logistics (Geodan, 2023c).
j) GeoSim Cities (Canada): A developer of high-resolution, data-rich 3D virtual cities, enabling digital twin applications by highly parametric models (GeoSim, 2023).

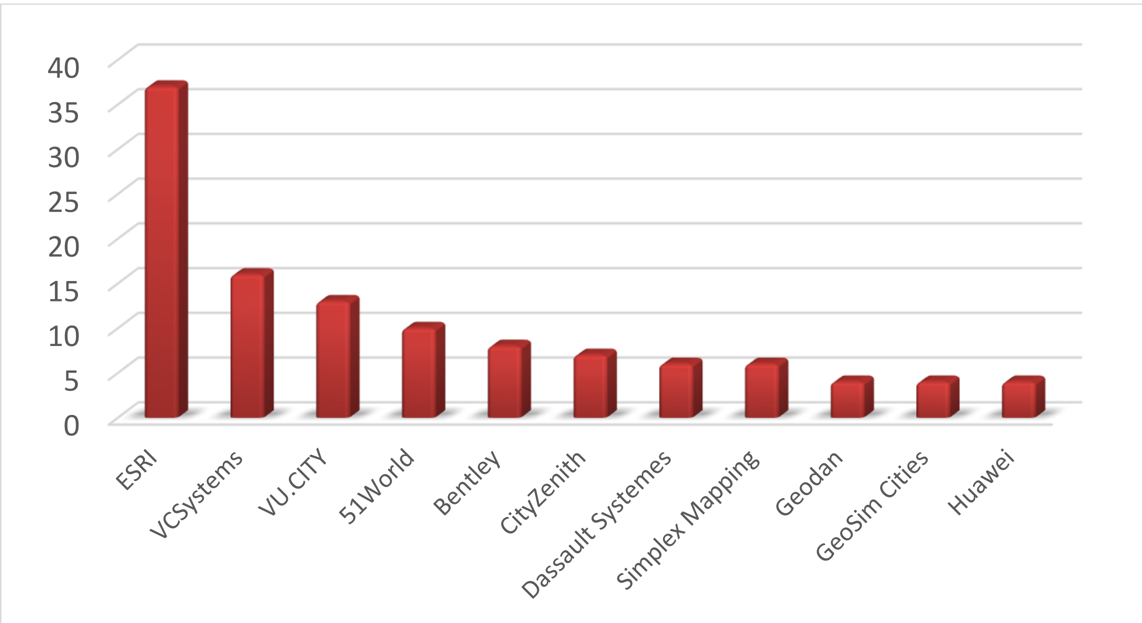


Fig. 3-14: Top companies in number of digital twin initiatives.

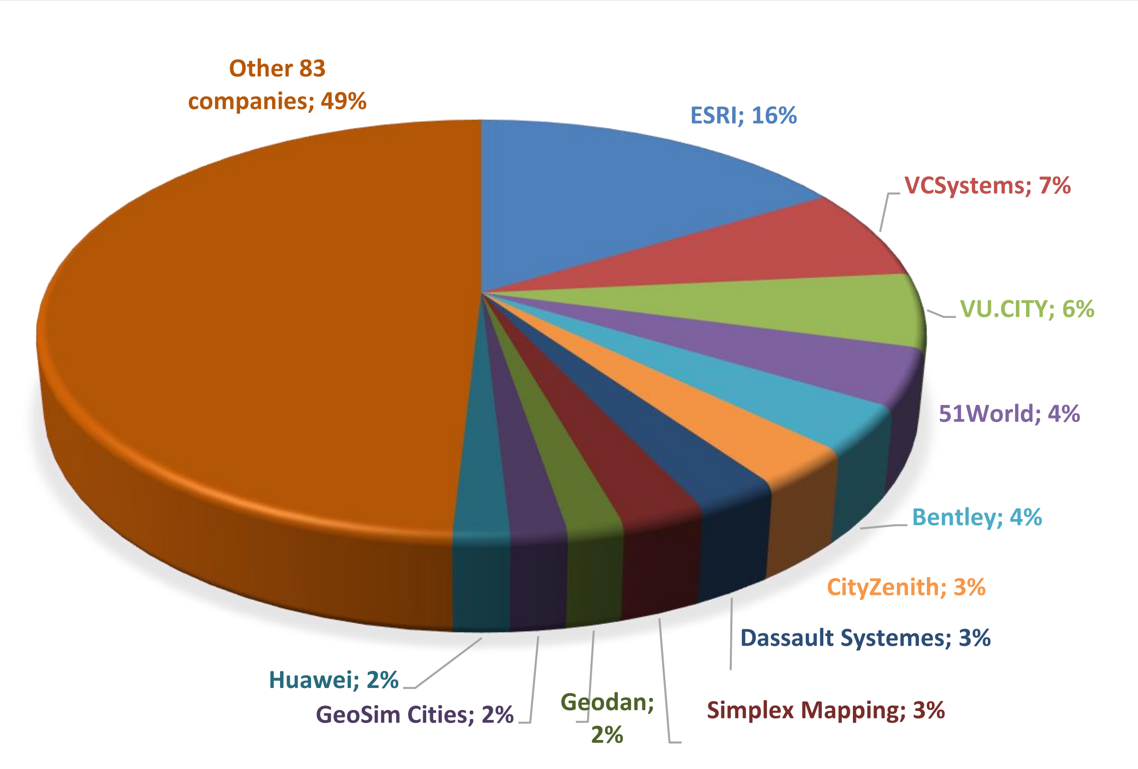


Fig. 3-15: Market share among assessed digital twins.

The geographic distribution of prominent digital twin operators reveals a widespread and global presence across numerous countries, reflecting the increasing significance and adoption of digital twin technology in various regions worldwide. With headquarters spanning the United States, Europe, Asia, and Australia, these companies emphasize the expanding reach and impact of digital twins in diverse contexts. The United States and the United Kingdom stand out as major hubs for spatial digital twin innovation, hosting multiple companies that actively contribute to the industry's growth and advancement. This highlights the commitment of these countries to invest in cutting-edge technology, shaping the future of urban planning and management.

Other European countries, such as Germany, France, and the Netherlands, also display their technological expertise by housing their own digital twin operators. China and Australia serve as examples of the Asia-Pacific region's involvement in the digital twin landscape, demonstrating the escalating interest and investment in smart city and infrastructure solutions in this region. This showcases the global nature of digital twin technology adoption.

3.4 Maturity Level Findings

During the assessment, over 2500 3D city models from the following companies were identified: Presagis, CGTrader, TurboCG, META-Group, HERE Premier 3D Cities, Metromap and CyberCity3D. At this moment they don't match the chosen conditions to be considered digital twins, fitting into level 0 (reality capture) in the technology maturity level and not making it into DUET implementation maturity level scale. For this reason they were not included in this study. Nevertheless, the wide range of 3D city models available from these companies demonstrates the growing importance and adoption of 3D technologies for urban planning, visualization, and analysis. It also indicates a potential for exponential growth in the amount of digital twins in the coming years. The rest of this section regards only the 334 initiatives that qualified as digital twins.

Fig. 3-16 provides a breakdown of digital twin projects based on their technology maturity levels. The largest portion of projects, consisting of 150 instances or 45% of the total, are at level 1, which signifies that they consist mainly of a semantic dataset. Actual dedicated applications, categorized as level 2, make up 90 instances or 27% of the share. Real-time data capabilities, classified as level 3, are present in 79 projects or 24% of the total, reflecting an increased level of sophistication in data processing and analysis. Two-way integration (from physical to digital and vice-versa), denoted as level 4, constitutes a smaller portion, with 15 instances or 4% of the share, highlighting more advanced integration with external systems.

No projects currently fall within the most advanced "Autonomous" category, level 5. This indicates that fully autonomous spatial digital twin projects are yet to be realized in the industry. The data shows that a majority of the initiatives are still in the early stages and there is a gradual progression towards the use of more advanced technologies.

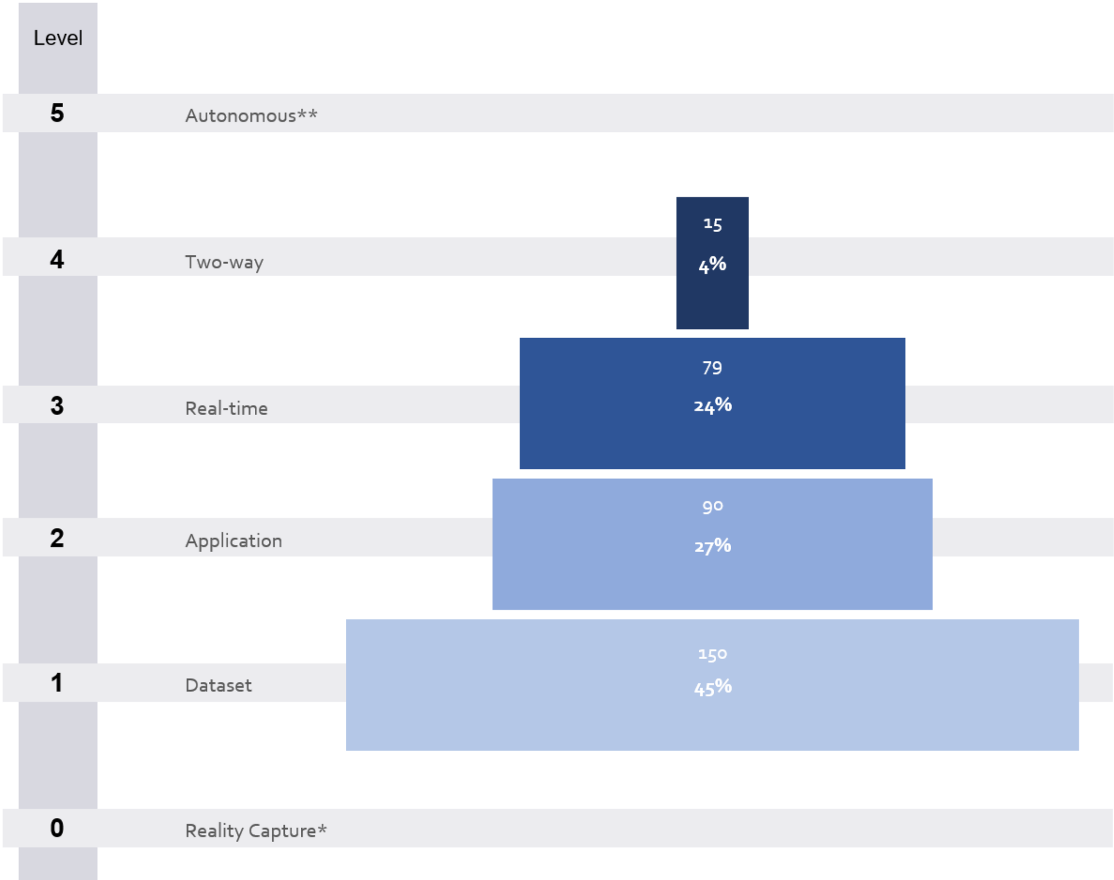


Fig. 3-16: Digital twins per technology maturity level.

Fig. 3-17 presents a comprehensive overview of digital twin projects classified according to the maturity level of the DUET (Digital Urban European Twins) framework. A majority of projects, comprising 174 instances or 52% of the total, fall under the "Experimental" category, highlighting the ongoing exploration and development phase for many digital twin implementations. "Insightful" projects, characterized by data-driven insights and enhanced decision-making capabilities, account for 87 instances or 26% of the share. Meanwhile, 53 projects or 16% of the total are still in the "Strategy" phase, denoting a focus on long-term planning and integration of digital twins into broader organizational objectives. Lastly, the most advanced "Intelligent" projects, which feature sophisticated AI-driven analytics and automation, constitute a smaller portion with 20 instances or 6% of the total share. This distribution reveals the varying maturity levels of digital twin projects, with a predominant focus on experimentation and gradual progression towards more advanced stages.

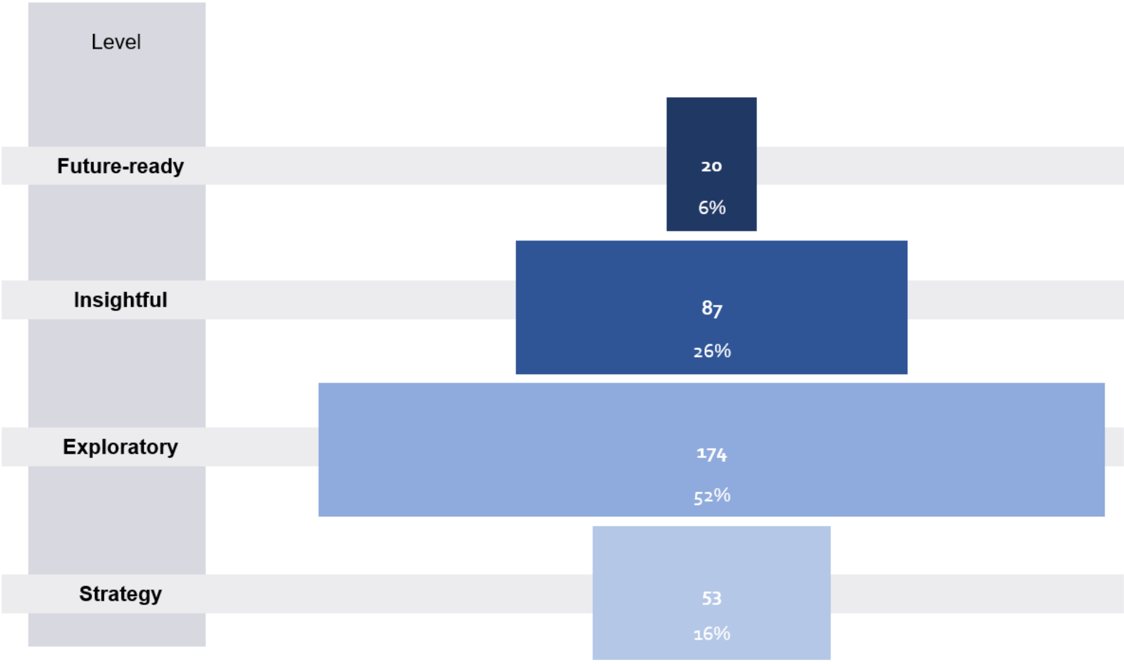


Fig. 3-17: Digital twins per implementation maturity level.

Table 3-3: Cross-table of digital twins per maturity level.

		Implementation/Outcomes			
		Strategy	Exploratory	Insightful	Future-ready
Technology	1 (dataset)	26 (7,8%)	117 (35,0%)	7 (2,1%)	-
	2 (application)	14 (4,2%)	37 (11,1%)	39 (11,7%)	-
	3 (Real-time)	13 (3,9%)	20 (6,0%)	40 (12,0%)	6 (1,8%)
	4 (Two-way)	-	-	1 (0,3%)	14 (4,2%)
	5 (Autonomous)	-	-	-	-

Table 3-3 offers a quantitative view of digital twin initiatives based on their maturity levels in the context of the technology and implementation stages. The percentages are calculated in relation to the total of assessed projects. A majority of projects are in the early stages, specifically in the Strategy and Exploratory stages. The concentration of projects at these stages, primarily staged in the first two levels of the scale, suggests that many organizations are still laying the groundwork for more advanced digital twin implementations.

As maturity levels increase, there is a clear progression towards more sophisticated capabilities. In the Insightful stage, projects shift towards getting real-time data processing and analysis capabilities, indicating a growing interest in leveraging dynamic data for better decision-making. The Future-ready stage, characterized by two-way integration, reveals a smaller but significant number of projects that have successfully implemented advanced integration between physical and digital, demonstrating the trend of the real world being managed through digital twin applications.

Table 3-4: Breakdown of digital twins per maturity level and region.

Region	Africa	Asia	Europe	Latin America	Middle East	North America	Oceania	Total
Technology Maturity Level								
1 (Dataset)	1.3%	16.0%	57.3%	8.0%	5.3%	9.3%	2.7%	100%
2 (Application)	1.1%	13.3%	55.6%	6.7%	1.1%	15.6%	6.7%	100%
3 (Real-time)	-	29.1%	44.3%	6.3%	6.3%	8.9%	5.1%	100%
4 (Two way)	-	86.7%	13.3%	-	-	-	-	100%
Implementation Maturity Level								
Strategy	1.9%	34.0%	37.7%	1.9%	7.5%	11.3%	5.7%	100%
Exploratory	0.6%	12.6%	60.9%	8.6%	4.6%	10.3%	2.3%	100%
Insightful	1.1%	20.7%	49.4%	8.0%	2.3%	10.3%	8.0%	100%
Future-Ready	-	70.0%	20.0%	-	-	10.0%	-	100%

As seen in Table 3-4 above, Europe demonstrates a balanced distribution across technology maturity levels, which suggests that organizations in this region are actively exploring and implementing a wide range of digital twin technologies. In implementation maturity levels, Europe is particularly strong in the Exploratory stage, with 60,9% of the digital twins at this level in the world, indicating a thriving ecosystem for early experimentation. Asia stands out for its dominance in Two-way integration (level 4) with an impressive 86.7% share of all digital twins at this level, highlighting the region's focus on advanced digital twin applications involving control from the physical by the digital. Most digital twins in North America are still restricted to applications (level 2), with 15.6% of the projects in this category (just behind Europe), implying that organizations are primarily developing specific solutions for their digital twin needs. In implementation maturity, Latin America maintains a consistent distribution across technology and implementation maturity levels, replicating the European scenario, but without representatives at level 4 and future-ready. While having a smaller presence in the digital twin landscape, Oceania has the largest relative share of insightful digital twins among all regions, indicating that the initiatives are already producing meaningful outcomes.

Table 3-5: Breakdown of digital twins per maturity level and ownership.

Ownership	Academia	Private	Public	Unsure	Total
Technology Maturity Level					
1 (Dataset)	10.0%	29.3%	60.0%	0.7%	100%
2 (Application)	8.9%	18.9%	72.2%	-	100%
3 (Real-time)	-	19.0%	79.7%	1.3%	100%
4 (Two way)	-	26.7%	73.3%	-	100%
Implementation Maturity Level					
Strategy	12.1%	29.3%	58.0%	0.6%	100%
Exploratory	-	18.4%	80.5%	1.1%	100%
Insightful	-	25.0%	75.0%	-	100%
Future-Ready	3.8%	15.1%	81.1%	-	100%

According to the data on Table 3-5, public ownership has strongest presence in Real-time (level 3) at 79.7%. This suggests that public organizations are actively investing in digital twin technologies capable of processing dynamic data for improved decision-making. Private ownership has a consistent distribution across all technology maturity levels, indicating diversity in solutions used, but scoring high on both very basic digital twins (level 1) and more advanced (level 4). Academia's presence appears not to be significant among the most technologically-advanced digital twins. In implementation maturity levels, public ownership again dominates across all stages. It is particularly strong in the Future-Ready stage at 81.1%, highlighting the public sector's commitment to advanced digital twin deployments. Private ownership is more evenly distributed across the implementation maturity levels, with the highest concentration in the Insightful stage at 25%, revealing an emphasis on gaining valuable insights from digital twin technologies. Academia's presence is most significant in the Strategy stage at 12.1%, suggesting that academic institutions are primarily involved in the strategic planning and conceptualization of digital twin projects.

Table 3-6: Breakdown of digital twins per maturity level and scale.

Scale	City	District	Infrastructure	Region	Total
Technology Maturity Level					
1 (Dataset)	60.7%	22.0%	7.3%	10.0%	100%
2 (Application)	57.8%	14.4%	13.3%	14.4%	100%
3 (Real-time)	44.3%	19.0%	21.5%	15.2%	100%
4 (Two way)	40.0%	26.7%	33.3%	0.0%	100%
Implementation Maturity Level					
Strategy	58.0%	21.3%	10.9%	9.8%	100%
Exploratory	56.3%	13.8%	12.6%	17.2%	100%
Insightful	40.0%	20.0%	35.0%	5.0%	100%
Future-Ready	49.1%	22.6%	15.1%	13.2%	100%

Table 3-6 shows that while city digital twins present a decreasing number of initiatives in higher technology maturity levels, infrastructure digital twins have an opposite distribution. Probably because real-time and two-way integration is crucial in these applications. Districts have the second highest amount of digital twins on level 4 and regions have none, illustrating a classic case of growing complexity of representation and operation at higher spatial scales. In implementation maturity levels, City scale remains the dominant focus across all stages, with the strongest presence in the Strategy stage at 58.0%. This highlights that many city-scale digital twin projects are in the strategic planning and conceptualization phase. District scale exhibits an even distribution across the implementation maturity levels, with the highest concentration in the Future-Ready stage at 22.6%, suggesting a growing focus on advanced digital twin deployments at the district level. Infrastructure scale is most prominent in the Insightful stage at 35.0%, indicating most digital twins at this scale provide valuable outcomes. Region scale, on the other hand, is more active in the Exploratory stage at 17.2%, showcasing experimentation with digital twin applications.

3.5 Use Cases

The research identified 28 use cases among the 334 digital twins assessed. They are presented on Fig. 3-18. While each use case is unique, this classification makes it possible to map the distribution of use cases in relation to the other attributes assessed and compare the different initiatives. The following list presents the classification of use cases, ordered by their occurrence, along with the number of instances identified in parentheses:

a) *City Planning (127)*: digital twins guide a holistic approach to urban planning, taking into account factors such as population growth, transportation, land use, and zoning.

b) *3D Visualization (64)*: digital twins provide realistic, three-dimensional representations of cities, districts, infrastructure, and regions for better communication, understanding, and decision-making.

c) *City Management (41)*: digital twins enable city officials to monitor and manage urban operations, infrastructure, and services in real-time, leading to increased efficiency and improved quality of life for citizens.

d) *Community Engagement (36)*: digital twins facilitate public participation in urban planning and development processes by providing interactive, visual tools that make complex information easily accessible and understandable.

e) *Logistics Operation (30)*: digital twins optimize operations of great infrastructure hubs, such as airports and ports, as well as logistics by cities, simulating and analyzing transportation routes, traffic patterns, and delivery schedules.

f) *Environmental Monitoring (29)*: digital twins help monitor and analyze environmental factors such as air quality and water resources, supporting sustainable urban development and natural resource management.

g) *Transportation Planning (25)*: digital twins enable the planning and optimization of transportation networks, considering factors such as traffic flow, public transit, and pedestrian mobility.

h) *Transportation Management (20)*: digital twins provide real-time traffic monitoring and management, enabling efficient allocation of resources and improved traffic flow.

i) *Real Estate Customer Experience (18)*: digital twins offer immersive, virtual experiences of properties, enhancing customer engagement and promoting real estate sales.

j) *Crisis Management (17)*: digital twins support emergency response and disaster management by providing real-time situational awareness, enabling efficient resource allocation, and simulating various scenarios for effective planning.

k) *Infrastructure Management (16)*: digital twins facilitate the monitoring, maintenance, and optimization of infrastructure assets, leading to reduced costs, improved performance, and extended asset life.

l) *Data Insights (10)*: digital twins enable the analysis and visualization of complex datasets, helping decision-makers derive meaningful insights and make informed decisions.

m) *Infrastructure Planning (8)*: digital twins support the planning, design, and construction of infrastructure projects by simulating various scenarios and providing performance projections.

n) *Permitting (8)*: digital twins streamline the permitting process by automating documentation, facilitating communication via 3d visualization, and providing a centralized platform for all stakeholders.

o) *Energy Modelling (7)*: digital twins enable the analysis and optimization of energy consumption and generation within cities, districts, and infrastructure projects, promoting energy efficiency and sustainability.

p) *Measure Emissions (7)*: digital twins help monitor and manage greenhouse gas emissions, supporting climate action and environmental policy implementation.

q) *Shadow Analysis (7)*: digital twins analyze the impact of shadows from buildings and structures on surrounding areas, informing urban design and improving public spaces and habitability of housing units.

r) *Crowd Management (6)*: digital twins support the monitoring and management of pedestrian flow and crowd dynamics in public spaces, enhancing safety and user experience.

s) *Noise Analysis (5)*: digital twins model noise pollution and its effects on urban environments, informing noise mitigation strategies and urban planning.

t) *Cadaster (4)*: digital twins facilitate the management and visualization of cadastral information, improving the accuracy and accessibility of land records and property data.

u) *Public Health (4)*: digital twins enable the monitoring and analysis of public health data, supporting policy development, resource allocation, and the evaluation of interventions in case of pandemics or outbreaks.

v) *Vegetation Management (4)*: digital twins assist in the monitoring and maintenance of urban green spaces, enhancing the quality of urban environments.

w) *Asset Management (3)*: digital twins help optimize the lifecycle management of physical assets, from planning and acquisition to operation, maintenance, and disposal.

x) *Economic Development (3)*: digital twins inform economic development strategies by simulating and analyzing the potential impact of investments, policies, and infrastructure projects.

y) *Public Safety (3)*: digital twins support public safety initiatives by enabling real-time monitoring, risk assessment, and emergency response planning.

z) *Heritage (2)*: digital twins help preserve and showcase cultural heritage sites and artifacts by creating accurate, interactive, and immersive digital representations.

aa) *Infrastructure Design (1)*: digital twins enable the virtual design, testing, and optimization of big infrastructure projects, reducing costs, risks, and construction timelines.

bb) *Public Policy Monitoring (1)*: digital twins provide a platform for tracking and evaluating the effectiveness of public policies, ensuring that resources are allocated efficiently and desired outcomes are achieved.

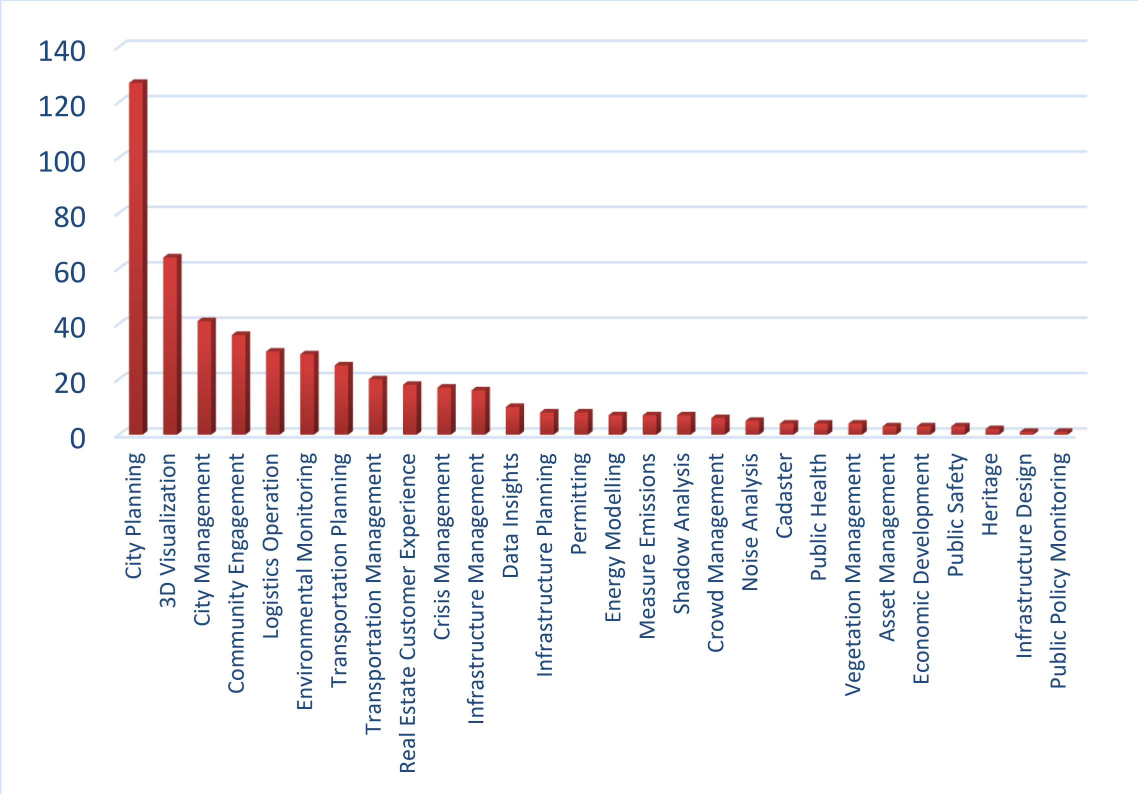


Fig. 3-18: Use cases for digital twins in number of occurrences.

Fig. 3-19 below illustrates the number of use cases per digital twin. Only one use case was identified in 61% of the digital twins, often city planning. In 29% of the digital twins two use cases were found, while only 8% and 2% of them integrate three and four use cases, respectively. The limited number of digital twins that address multiple use cases may indicate that most initiatives are still not taking full advantage of the potential of digital twins for multidisciplinary collaboration and cross-thematic insights.

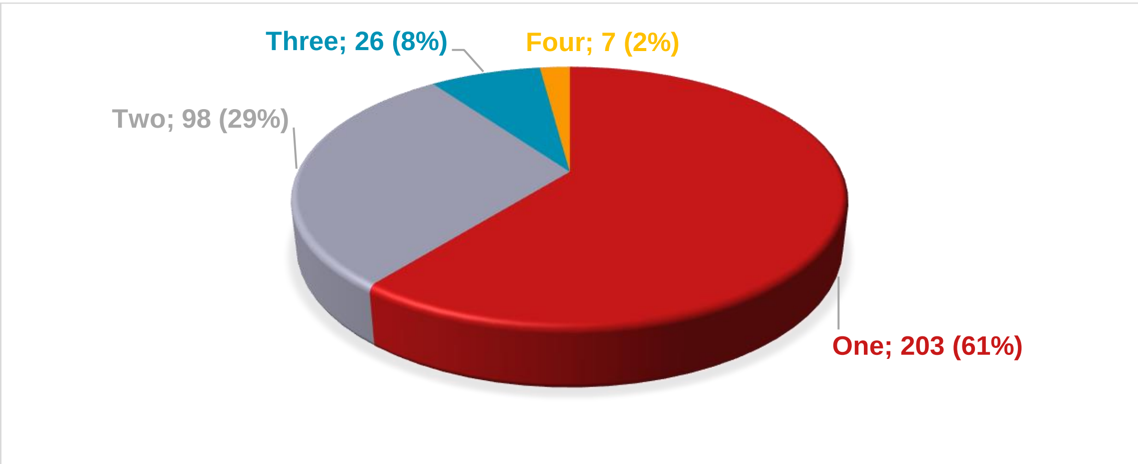


Fig. 3-19: Number of use cases per digital twin initiative.

Table 3-7: Most common use cases per world region.

AFRICA	
City Planning	67%
Logistics Operation	33%
ASIA	
City Management	22%
City Planning	19%
3D Visualization	10%
Logistics Operation	9%
EUROPE	
City Planning	24%
3D Visualization	13%
Community Engagement	7%
Logistics Operation	6%
LATIN AMERICA	
City Planning	45%
3D Visualization	10%
Infrastructure Management	10%
MIDDLE EAST	
City Planning	32%
3D Visualization	28%
City Management	8%
NORTH AMERICA	
City Planning	19%
3D Visualization	13%
Real Estate Customer Experience	11%
OCEANIA	
City Planning	25%
Community Engagement	15%
Environmental Monitoring	15%

The table 3-7 above shows the distribution of the most common use cases for digital twins across different regions. In Africa, City Planning (67%) and Logistics Operation (33%) are the most prevalent use cases. In Asia, City Management (22%), City Planning (19%), 3D Visualization (10%), and Logistics Operation (9%) are the top applications. Europe exhibits a more diverse range of use cases, with City Planning (24%), 3D Visualization (13%), Community Engagement (7%), and Logistics Operation (6%) being the most common. In Latin America, City Planning (45%) is the dominant use case, followed by 3D Visualization (10%) and Infrastructure Management (10%). The Middle East also has City Planning (32%) and 3D Visualization (28%) as the leading use cases, with City Management (8%) being the third most common. North America features City Planning (19%), 3D Visualization (13%), and Real Estate Customer Experience (11%) as the main use cases. Lastly, in Oceania, the top use cases are City Planning (25%), Community Engagement (15%), and Environmental Monitoring (15%).

This data reveals unique patterns in certain regions. The higher prevalence of City Management in Asia might be driven by the higher maturity level of digital twins, which are often enabled with real-time data collection and processing and centralized governments. On the other hand, the higher emphasis on Real Estate Customer Experience in North America may be linked to the region's developed and competitive real estate market and the increasing demand for sophisticated customer engagement tools. It also reflects the important role of the private sector in urban development and planning in this region.

In Table 3-8, we see the most common use cases for digital twins at different scales: Infrastructure, District, City, and Region levels. At the Infrastructure level, Logistics Operation (63%) is the predominant use case, followed by Infrastructure Management (13%) and Transportation Management and Planning (7% each). District level use cases are led by City Planning (28%), City Management (11%), and Transportation Management, 3D Visualization, and Energy Modelling (8%, 8%, and 7% respectively). City-level digital twins mainly focus on City Planning (30%), 3D Visualization (15%), City Management (10%), and Community Engagement (7%). Lastly, Region-level use cases include City Planning and 3D Visualization (15% each), Environmental Monitoring (12%), and Data Insights (8%).

Table 3-8: Most common use cases per scale.

INFRASTRUCTURE-LEVEL	
Logistics Operation	63%
Infrastructure Management	13%
Transportation Management	7%
Transportation Planning	7%
DISTRICT-LEVEL	
City Planning	28%
City Management	11%
Transportation Management	8%
3D Visualization	8%
Energy Modelling	7%
CITY-LEVEL	
City Planning	30%
3D Visualization	15%
City Management	10%
Community Engagement	7%
REGION-LEVEL	
City Planning	15%
3D Visualization	15%
Environmental Monitoring	12%
Data Insights	8%

Upon deeper analysis, we notice that certain use cases are unique to specific scales. For instance, Logistics Operation is primarily observed at the Infrastructure level, considering that these dynamic models are very important to infrastructure. Energy Modelling is predominantly found at the District level, likely due to its relevance and feasibility in assessing energy consumption and efficiency within a concentrated urban space. In contrast, Environmental Monitoring and Data Insights are more prominent at the Region level, highlighting the need for a broader perspective when addressing environmental concerns and leveraging data for decision-making.

Table 3-9: Most common use cases per ownership.

ACADEMIA	
City Planning	27%
Energy Modelling	23%
Community Engagement	15%
PRIVATE	
3D Visualization	34%
Logistics Operation	25%
Real Estate Customer Experience	17%
PUBLIC	
City Planning	29%
City Management	11%
Community Engagement	8%
3D Visualization	7%

Digital twin ownership also plays an important role when guiding the use cases, as shown in the Table 3-9 above. In the academia, the most common use cases are City Planning (27%), Energy Modelling (23%), and Community Engagement (15%). This indicates a focus on research and development in urban planning, energy efficiency, and fostering communication with the community. In the private sector, the primary use cases are 3D Visualization (34%), Logistics Operation (25%), and Real Estate Customer Experience (17%). This suggests that private organizations leverage digital twins primarily for visualization purposes, optimizing logistics processes, and enhancing customer experience in the real estate market, ultimately aiming to increase efficiency and drive profitability. Finally, in the public sector, the leading use cases are City Planning (29%), City Management (11%), and Community

Engagement (8%), with 3D Visualization following closely (7%). This demonstrates the public sector's interest in utilizing digital twins for improving urban planning and management, while also fostering citizen participation in decision-making processes.

Table 3-10: Most common use cases on 3D and not-3D digital twins.

3D	
City Planning	29%
3D Visualization	15%
Community Engagement	7%
NOT 3D	
City Management	23%
Environmental Monitoring	19%
Transportation Planning	14%

As expected, 3D and not-3D digital twins are used for different purposes. As presented in Table 3-10, among 3D digital twins, the most prevalent use cases are City Planning (29%), 3D Visualization (15%), and Community Engagement (7%). This highlights the value of 3D digital twins in providing a comprehensive, visually immersive representation of urban spaces, facilitating better planning and decision-making, and fostering public involvement in urban development projects. On the other hand, among non-3D digital twins, the leading use cases are City Management (23%), Environmental Monitoring (19%), and Transportation Planning (14%). This suggests that non-3D digital twins are suited for data-intensive applications, in which an immersive visualization is less important.

As presented in Table 3-11 below, at the technology maturity level, the use cases vary significantly. For level 1, 3D Visualization is the most common use case, accounting for 35% of projects. As the maturity level increases, City Planning becomes the most prominent use case for level 2 (30%), while City Management leads level 3 and level 4 with 18% and 33%. Logistics Operation shows up in the ranking on level 3 and 4. This indicates that as technology matures, digital twins are increasingly used for more advanced city management and logistics operations. In terms of implementation maturity, City Planning is the top use case across the Strategy (24%), Exploratory (29%), and Insightful (22%) levels. However, at the Future-ready level, City Management takes the lead with 28%, followed by Logistics Operation at 16%. This suggests that as implementation maturity progresses, digital twins become more adept at handling complex city management tasks and streamlining logistics operations.

Table 3-11: Most common use cases on digital twins in different maturity levels.

TECHNOLOGY MATURITY LEVEL							
Level 1		Level 2		Level 3		Level 4	
3D Visualization	35%	City Planning	30%	City Management	18%	City Management	33%
Community Engagement	9%	Community Engagement	10%	Environmental Monitoring	12%	Logistics Operation	17%
Real Estate Customer Experience	9%	Logistics Operation	7%	Logistics Operation and City Planning	11% each		
IMPLEMENTATION MATURITY LEVEL							
Strategy		Exploratory		Insightful		Future-Ready	
City Planning	24%	City Planning	29%	City Planning	22%	City Management	28%
City Management	13%	3D Visualization	22%	City Management	11%	Logistics Operation	16%
Logistics Operation	11%	Real Estate Customer Experience	5%	Community Engagement	8%		

3.6 Conclusions

Based on the publicly-available online information, it is possible to state that the present global assessment of digital twins is up to the date of this publication the most comprehensive in the world and it provides unique and unprecedented insights into the development of this important technology breakthrough. Still some research limitations remain: the online material available in West-European languages was more explored than in Eastern languages, leading to possible underrepresentation of the latter. The maturity level and use cases analysis of digital twins can be subjective, given that many of these projects have limited documentation available and the assessment of such technology is relatively new.

While most digital twins are owned by the government and a significant number is operated by the government, very few of them are really open-source, providing their code to the public. It suggests that the development of digital twins is still taking place quite independently in the different organizations, with limited peer collaboration.

Varying from one to four, the use of digital twins to cross-multidisciplinary use cases is still limited. It probably happens because the design of digital twins replicate the silos in their organizations, since the use cases match typical city departments, such as city planning, environmental protection, mobility and so forth. Leveraging digital twins to address a broader range of use cases can result in more comprehensive and adaptable solutions, ultimately enhancing the benefits and efficiency derived from such technologies.

In summary, the data reveals an industry in transition, with a majority of projects in the early stages of maturity and technology implementation. As organizations progress along the maturity spectrum, there is a clear shift towards more advanced capabilities, such as real-time data processing and two-way integration. The current absence of autonomous digital twin projects highlights the potential for continued growth and innovation in the field, as the industry strives to realize the full potential of digital twin technology. Is it also still an important discussion on how far do we want to go with digital twin autonomous operations.

The breakdown by region suggests that the focus of digital twins are highly influenced by the unique socioeconomic, political and cultural contexts of each region. Understanding these patterns can help guide the development and implementation of national and international digital twin policies. The diversity in use cases and meaningful predominance of digital twins at an exploratory level in Europe, for example, reflects the funding available from national governments and the European Union for research, but it ranks lower in maturity level when compared to Asia. It indicates that there are some difficulties to scale up and implement integral digital twin solutions in the continent.

The analysis reveals that the choice between 3D and non-3D digital twins depends on the specific objectives and requirements of the project. While 3D digital twins excel at providing detailed visualizations and enhancing stakeholder engagement, non-3D digital twins are better suited for data-intensive applications, such as monitoring and management tasks. Recognizing the strengths and limitations of each approach is crucial for selecting the appropriate technology to meet the goals of a particular project.

By providing an in-depth exploration of the state-of-the-art of spatial digital twins all around the world, this thesis equips readers with a thorough understanding of these initiatives and their capacity to revolutionize urban management, planning, and sustainability. By evaluating and learning from global experiences, we can harness the power of digital twins to create more resilient, efficient, and sustainable cities for the future. The next chapter presents a deeper study of the digital twin ecosystem in the Netherlands.

3.7 References

51World. (2023). *51World*. https://www.51world.com.cn/

Atkins. (2019). Digital twins for the built environment an introduction to the opportunity, benefits, challenges and risks. *BIMToday*.

Bentley. (2023). *Improving the Environment with a city-scale digital twin*. https://www.bentley.com/company/esg-user-project-city-of-helsinki/

Cityzenith. (2023). *World Leading Urban Digital Twin Technology*. https://cityzenith.com/

Dassault Sistèmes. (2023). *Virtual Twin Experiences in Infrastructure & Cities*. https://www.3ds.com/virtual-twin/infrastructure-cities

DUET. (2022a). *About us*. https://www.digitalurbantwins.com/about-1

DUET. (2022b). *Digital Twin Maturity Model*. https://www.digitalurbantwins.com/digitaltwinmaturitymodel

ESRI. (2023). *Digital Twin*. https://www.esri.com/en-us/digital-twin/overview

Geodan. (2023). *What is a Digital Twin?* https://www.geodan.com/products-and-services/local-government/digital-twin/

GeoSim. (2023). *The Ultimate in Digital Twin Technology*. https://geosimcities.com/

Simplex Mapping. (2023). *Make your city come alive*. https://www.simplex-mapping.com/

VCSystems. (2023). *Digital Views, Real Perspectives.* https://vc.systems/en/

VU.City. (2023). *How it works*. https://www.vu.city/how-it-works

4 Digital Twin Ecosystem in the Netherlands[2]

This chapter presents an overview of the applications and status of digital twins for the built environment in the Netherlands. It aims to provide an introduction to the Dutch context of spatial planning, an overview of public and private initiatives for digital twin applications and to draw insights from selected case studies, especially regarding technical solutions, governance, stakeholders and challenges. Jacobides et al. (2018) provide a definition of *ecosystem* that fits the context of information systems: “a set of actors with varying degrees of multilateral, non-generic complementarities that are not fully hierarchically controlled”. This definition applies to the ensemble of actors of the Dutch digital twin ecosystem.

4.1 The Dutch Spatial Planning Context

The Netherlands have a long tradition in assessing and monitoring changes in the built environment through the implementation of reliable spatial and non-spatial databases. Founded in 1832, the Dutch cadaster organization, Kadaster, began with the measurement of land for tax purposes. After 1885, a nationwide triangle network was implemented as an effort to match the assessments of different cities and over the years, it grew to the important entity that it is today (Kadaster, 2023b). Having an autonomous national entity dedicated to the cadaster was an important step for territorial management in a relatively small country politically divided into provinces and municipalities of different kinds.

The Kadaster holds publicly accessible datasets on multiple topics. Some of these datasets consolidate information about assets nationwide (i.e. roads, bridges, buildings) and are known as *basisregistraties*, containing the following information (Kadaster, 2023a):

[2] This chapter was partially published by the author on 6 Dec 2022 at the Smart Cities in Smart Regions 2022 Conference Proceedings with the title *State-of-the-Art of the Urban Digital Twin Ecosystem in the Netherlands*. It is accessible at https://research.tue.nl/en/publications/state-of-the-art-of-the-urban-digital-twin-ecosystem-in-the-nethe

- *Basisregistratie Adressen en Gebouwen* (BAG): registers year of construction, surface area, purpose of use and location of all the buildings in the country. Municipalities are responsible for including the data and assuring its quality;
- *Basisregistratie Kadaster* (BRK): consists of the cadastral registration of immovable property and the cadastral map. It shows the location of the cadastral parcels (including parcel number) and the boundaries of the national government, the provinces and the municipalities.
- *Basisregistratie Topografie* (BRT): consists of digital topographic files at different scale levels. Both the formatted maps and the object-oriented files are available as open data. This means that Kadaster makes these data files available free of charge and subject to minimum delivery conditions.
- *Basisregistratie Grootschalige Topografie* (BGT): is a detailed digital map of the Netherlands. In the BGT, objects such as buildings, roads, water, railways and greenery are recorded in an unambiguous way.

For good policy and management, some governmental entities and partner companies are currently developing the *Basisregistratie Ondergrond* – BRO (BZK, 2023a), a central registry with public data on the Dutch subsurface. From one central digital place, the national facility, users will be able to request data for information about soil and subsoil. Elements such as cables and sewage systems are not included in the BRO. They are therefore not fully digitized, standardized and harmonized to the same extent and are only partially publicly available. Current challenges such as energy transition, climate change adaptation and housing provision have an enormous impact also below the ground. It is therefore essential to gain a spatial and integral insight into the subsurface.

Taking advantage of the possible integration of plenty of existing databases about various aspects of the territory, the *Omgevingswet*, the new Dutch environmental code, will join 26 regulations into one code in order to simplify the permitting processes. This new regulatory framework requires multiple datasets to be accessible for different stakeholders, enabling them to perform technical analysis and provide quick insights about new proposed buildings, companies and activities (IBR, 2023). It simplifies the legal framework applicable to changes to the physical living environment, like a new farm of solar panels, new wind turbines or housing renovation. It requires unprecedented integration of public datasets and procedures within public entities to provide timely and efficient response to permit applications.

Even if energy efficiency and migration to sustainable energy sources is a high-level goal of international agreements, sometimes local regulations can make it more difficult for these changes to be implemented in the territory within a reasonable timeframe. The aim of this regulation is to achieve a balance between protecting the physical living environment, ensuring a safe and healthy physical living environment and good environmental quality, and making use of the physical living environment, developing the physical living environment based on social needs. While following the policy principles, the core instruments offer plenty of practical opportunities for the use of digital twins.

The main principles of this policy are (Interprovinciaal Overleg, 2023):

- Insightful environmental law: it must be transparent, predictable and easy to use. In the design of the legal system, the policy cycle was used to assess which different instruments are needed in the various phases of the process.
- Living environment at the center: the living environment is coherently central to policy, decision-making and regulations. The physical living environment concerns, for example, buildings, infrastructure, the environment and heritage.
- Room for local customization: the policy offers governments more flexibility in order to achieve goals for the living environment in what it calls *policy space*. The act aims to strengthen the position of local and regional authorities, decentralizing whatever is possible to decentralize. This means that municipalities are authorized to draw up rules, unless there is an overarching interest.
- Faster decision-making: decision-making about projects impacting the built environment is faster and better under the *Omgevingswet*, requiring an integrated and coherent working method on the part of governments, citizens and companies. For many permits, the regular procedure will apply with a decision period of 8 weeks.

The *Omgevingswet* intends to protect the environment by applying the six core instruments (Interprovinciaal Overleg, 2023):

- *Omgevingsvisie* (Environmental Vision): a coherent strategic plan about the living environment, including all sectorial views. The national government, as well as each province and municipality in the Netherlands must establish one single plan for their entire territory.
- *Programma* (Program): an action plan containing measures for the protection, management, use and development of the built environment. Municipalities, water boards, provinces and the central government formulate measures in programs that lead to the desired quality of the physical living environment, making use of policy rules and financial instruments. Table 4-1 below presents the differences between the *Omgevingsvisie* and the *Programma*.

Table 4-1: Differences between the Omgevingsvisie and the Programma.

	Omgevingsvisie	**Programma**
Character	Strategic, integral, political-administrative	Implementation-oriented, (multi-) sectoral, strategic elements possible
Content	Development, use, management, and preservation of the physical living environment as a whole	Elaboration of a policy for a specific sector or specific area
Coherence between domains	One integrated development policy for the physical living environment	(Multi-) Sectoral, focusing on coordination, coordination of various domains
Horizon	Long-term	Short-term
Operation	Basis for the actions of the vision-determining administrative body and for programs	Basis for deployment of measures on the subject in question
Juridical status	Only binds the vision-determining entity (self-binding)	Only binds the program determining body (self-binding)
Determination	Municipal Council, Provincial Council or the Minister of the Interior and Kingdom Relations (BZK)	Municipal Executive, general board of the Water Board, Provincial Executive or Minister Concerned

- *Decentrale Regels* (Decentralized Rules): local authorities have one single scheme for the environment in their entire territory: *gemeentelijk omgevingsplan* (municipal environmental plan), provinciale omgevingsverordening (provincial environmental regulation) and the waterschapsverordening (water board regulation). It contains more specific rules regarding allowed activities and areas that have a specific function.
- *Algemene Rijksregels voor Activiteiten* (General Rules for Activities): Most activities in the living environment are initiatives of citizens and companies and general government regulations apply to some of these activities. As a result, citizens and companies do not always have to ask for permission from the government. The disadvantage of general rules is that they sometimes do not fit well with a specific situation. That is why there are possibilities in the law to deviate from the general rules under certain conditions.
- *Omgevingsvergunning* (Environmental Permit): when initiatives made by citizens and companies have potential consequences to the environment, a permit is required. The government checks in advance whether this is allowed. The assessment must be simple taking into account the general rules, preventing rules from contradicting or getting in the way. With this policy, the initiator makes one application at one counter.
- *Projectbesluit* (Project Decision): a special procedure enabling projects with a public national, provincial, municipal or water board interest, consisting of 5 steps. The second step establishes rules and space for citizens, companies and social organizations to influence a project decision at an early stage. For the central government, provinces and water boards, the final step is a *Projectbesluit*. For municipalities, the final step is an adjustment of the *Omgevingsplan*.

As a step on *Omgevingswet* implementation, the Dutch central government issued the *Nationale Omgevingsvisie* (NOVI), indicating the challenges faced, what the national interests are and what choices were made and what direction to give to decentralized choices. These are the main policy choices in the NOVI: a climate-proof design of the Netherlands; the change in energy supply; the transition to a circular economy; the development of the *Stedelijk Netwerk Nederland* (an accessible network of cities); placing so-called logistics functions together (for example distribution centers, data centers) in order to maintain the openness and quality of the landscape; future-proofing the rural area in a good balance with nature and landscape (BZK, 2023b).

In this context, the governmental organization responsible for geographic studies and standards, Geonovum, has proposed a National Digital Twin for the Built Environment (*Nationale Digitale Tweeling van de Fysieke Leefomgeving* - DTFL), that could be used as public set of instruments by governments, citizens, companies and knowledge institutions, exploring societal challenges in the physical living environment and designing and developing solution scenarios. It will consist of a federated set of agreements around three components (Geonovum, 2021a):

- The sum of regional, thematic or urban DTFLs: have been developed to address a social issue in the physical living environment. These DTFLs are connected to each other. New DTFLs can use already existing functionalities and enriched source data and models and continue to build, knowing that ingredients from a reliable DTFL Infrastructure might become available. In this way, the knowledge surrounding the assignments is shared as much as possible.
- The DTFL infrastructure: built on top of the existing National Geoinformation Infrastructure, enables sharing of source data, models and visualizations possible. The DTFL infrastructure provides access routes to all kinds of sources and applicative services and interfaces, ensuring a reliable National set of ingredients for a DTFL.
- The practice of Digital Twinning is brought together in the DTFL ecosystem. The DTFL ecosystem provides the components surrounding the development and use of a DTFL such as a set of conditional standards, quality marks and instruments to guarantee meaningful, predictable and transparent use within a context of rules for public values.

The National DFTL adopts a value-driven approach, endorsing and representing social complexity, oriented towards four goals (Geonovum, 2021a):

- Realization of solutions for societal challenges by using the digital twin as an instrument. Field Labs will be set up with 'Quadruple Helix' coalitions (government, citizens, companies and knowledge institutions) to identify possible solutions using a DTFL.

- Forming collaborations with other initiatives developing thematic DTFLs, for example around mobility, the built environment and infrastructure assets. Commitment from these parties to include these DTFLs and the associated data and models ('dataspace') in the National DTFL is crucial to the success of the project.
- Unlocking knowledge from private initiatives and Field Labs. The developed DTFLs are broken down into recipes consisting of the ingredients; data, calculation models and technology.
- Developing an ecosystem of users. Everything must be secured in the National DTFL, a federated entity in which specific DTFLs are linked. To that end, it is important to train those directly involved in the development and use of the DTFL based on the foundation of public values. This requires community management to create a demand for good training, based on success stories from practice.

4.2 Digital Twins Assessment Methodology

Comparing different initiatives in such an innovative field as digital twinning can be challenging. Therefore a method was developed to frame the main technical and administrative aspects of the projects. Aiming to better understand the Dutch digital twin landscape, the adopted method for this research follows four steps: 1) finding digital twin initiatives via searching organizational websites; 2) developing a digital twin assessment template based on academic and practical literature; 3) identifying digital twin project leaders for conducting interviews for data collection; 4) consolidating the collected qualitative data from the interviews and drawing conclusions.

The Digital Twin Assessment Template (**Appendix**) was designed in order to document the different digital twin projects in the Netherlands in comparable aspects. The document consists of some dozens questions organized in the following sections: a) respondents; b) city/region data; c) administrative conditions, d) entities and their role in the digital twin ecosystem; e) quadruple helix engagement; f) technologies adopted; g) project development process; h) final remarks.

Table 4-2: Conducted interviews.

Name of the Project	Type of Initiative	Respondents	Affiliation	Date of Interview
Brainport Smart District (BSD)	Private	Tom van Tilburg (Senior Researcher) and Janne Verstappen (Business Consultant)	Geodan	07/05/2021
Lekdijk Digital Twin	Public	Peter de Graaf (Business Consultant)	Geodan	18/05/2021
3D Amsterdam	Public	Wietse Balster (Product Owner)	City of Amsterdam	08/06/2021
Rotterdam 3D	Public	Roland van der Heijden (Program Manager)	City of Rotterdam	17/06/2021
3D Utrecht	Public	Frans de Waal (Software Architect)	City of Utrecht	18/06/2021
Groningen 3D Digital City	Public	Leontien Spoelstra (3D GIS Specialist - Product Owner)	City of Groningen	25/06/2021
Digitwin	Private	Jeroen Steenbakkers (Company Owner)	Argaleo	05/07/2021
Tygron Platform	Private	Florian Witsenburg (CEO)	Tygron	14/07/2021
Future Insight Digital Twins	Private	Rick Makkinga (Project Leader)	Future Insight	14/07/2021
Eindhoven Stadsmodel	Public	Michiel Oomen (Digital Innovation Program)	City of Eindhoven	22/09/2021

Since there are not many complete and publicly accessible documentations of the digital twin initiatives on-line, the projects were assessed by interviews lasting around one and a half hour with key professionals involved in each digital twin initiative. The majority of questions posed to stakeholders were open-ended in order to enable a deeper qualitative understanding of the different projects.

The 10 interviews were conducted with the professionals between May and September 2021. Table 4-2 above presents more information regarding the interviews. While 40% of interviewees played a mainly technical role in the project, 60% had a mainly managerial position. All of the interviewees had sufficient knowledge of both managerial and technical aspects of the projects they were involved in.

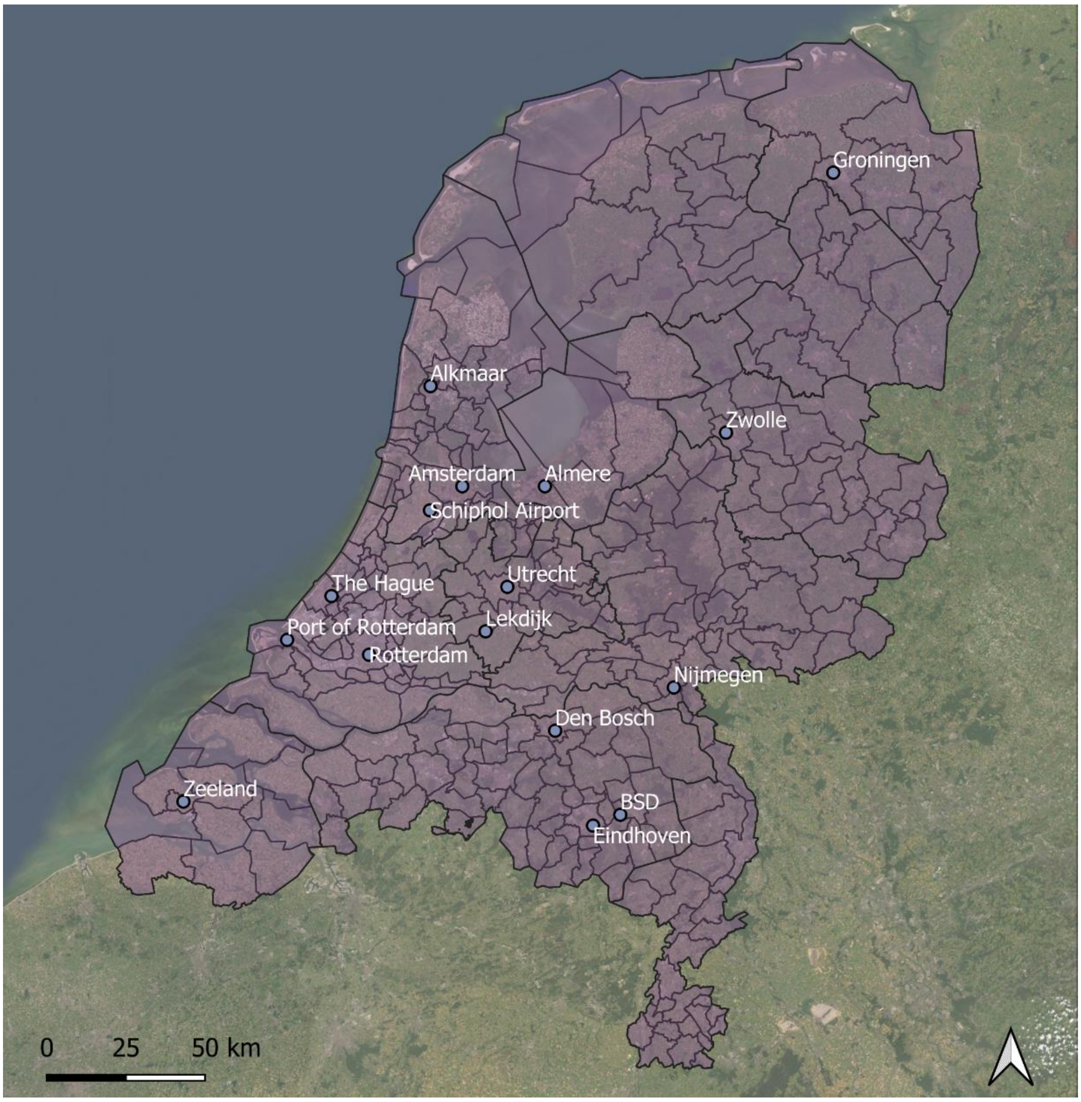


Fig. 4-1: Overview of Dutch local digital twin initiatives.

4.3 Digital Twins in the Netherlands

This section presents information about digital twin initiatives undertaken by both the public and the private sector in the Netherlands based on the conducted interviews. The following aspects were included in the scope of the research: general information about the project or company, timeframe, management model, use cases, challenges and next steps.

4.3.1 Public Initiatives

The Dutch capital Amsterdam is known for its vibrant innovation ecosystem. The city is home to institutions like the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), which undertakes innovation projects as a response to contemporary urban challenges. The municipal government holds a department for innovative solutions and *3D Amsterdam* is one of their projects. Starting in April 2019 with a budget of about €650.000, the aim of *3D Amsterdam* platform is to enable an interactive 3D city experience.

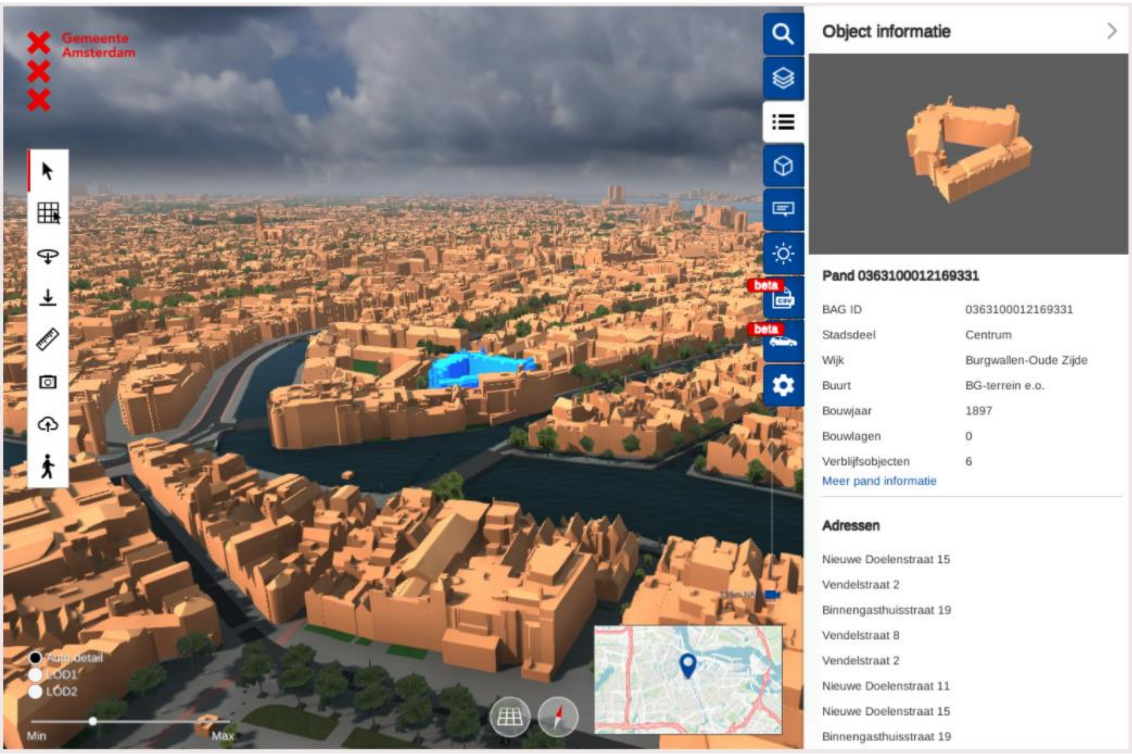


Fig. 4-2: 3D Amsterdam web-viewer.

The main goals of this project are: (i) providing information about the city, (ii) making communication and participation more accessible through visuals, (iii) viewing and sharing 3D models. Overtime, more data is embedded into the model so that in the future it is expected that an array of simulations and the visualization of solar and wind studies will be possible. *3D Amsterdam* viewer (Fig 4-2 below) is based on the game-engine Unity and the open-source software code is publicly available at a GitHub repository (Gemeente Amsterdam, 2023).

The municipal government of Utrecht partnered up with Amsterdam to cooperate in the development of the same web-viewer, in an effort to provide better visualization of the datasets regarding the built environment in the city. The full digital twin architecture is under development by the municipality, linking three use cases that currently use different platforms: heritage protection and visualization, building asset management and crowd management.

Fig. 4-3: 3D Utrecht web-viewer.

Rotterdam, the second largest city in the Netherlands, hosts the most comprehensive municipal digital twin project in the country. Starting in January 2018 within the Digital City Program with a budget of over €2.000.000, the 3D

Digital Twin is a tridimensional registry of buildings, vegetation, urban furniture and other physical elements.

By working together with various other parties in pilot projects, a Open Urban Platform is being put together step-by-step. Creating a set of interoperable modules can be considered a different approach in comparison to other municipalities, where the specific stand-alone applications are developed to meet specific needs. Some use cases under development for Rotterdam's digital twin are (Gemeente Rotterdam, 2023):

- A co-creation app enabling participation and discussion in spatial planning. Residents will be able to make proposals themselves and submit them to the municipality without needing to attend events at a specific time and place. Possible costs or physical obstacles to interventions can also be taken into account immediately.
- Streamlining the permitting process by creating an application that supports the submission of 3D models. By converting some of the rules and agreements into code, submitting an application becomes more efficient and the municipality can test and make a decision more quickly, using regulation model checkers.

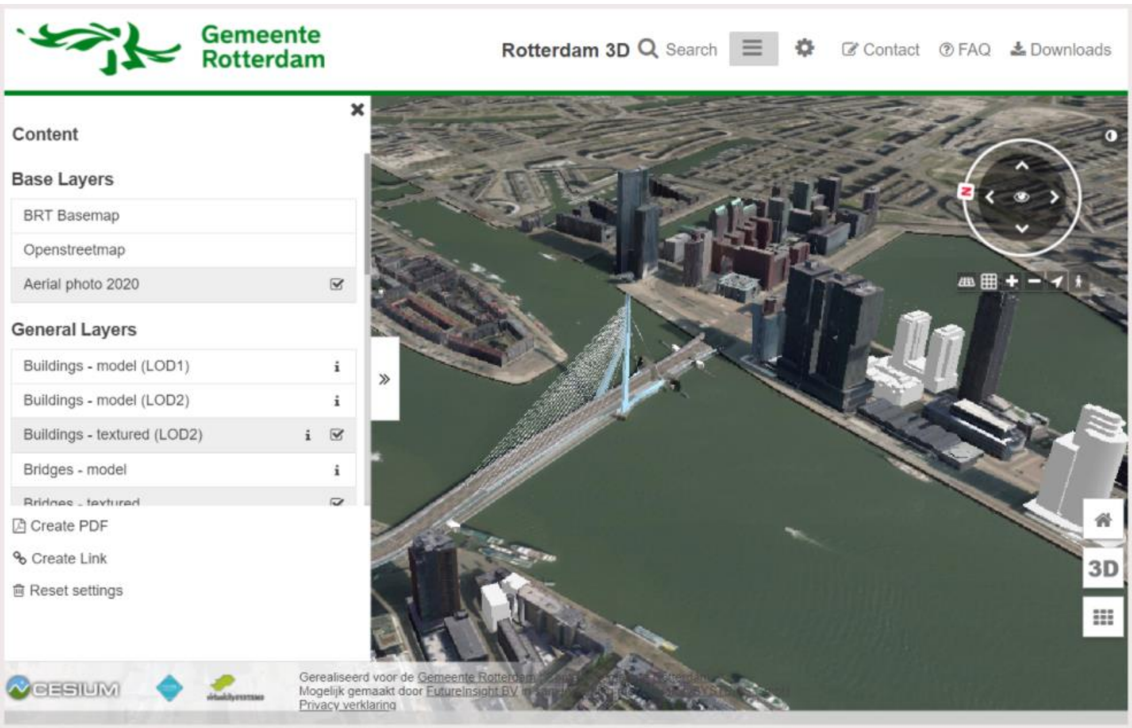


Fig. 4-4: Rotterdam 3D web-viewer.

- Safe Rotterdam 3D is a program that aims to increase safety in and around buildings by creating a 3D version of buildings and their environments and getting the government more prepared in the case of an emergency.
- An application to gather 3D building information in new construction projects for communication and promotional purposes. With Augmented Reality, the end result can be made visible on the construction site before (and during) a construction project. By scanning a code with a smartphone, the planned building becomes visible in reality in full size.

In Eindhoven, a 3D model of the city center was developed in 2019 in the scope of a larger sustainable urbanization study that compared scenarios of densification of the city core. The ESRI solution ArcGIS Urban was chosen because it could deliver quick visualization of the datasets. Developed at the value of a proof-of-value, the model allowed for simulation of urban parameters and visualization of available datasets in order to draw insights from different proposed scenarios for the region (ESRI, 2021).

The initiative is also linked to a long-term collaboration effort between around 20 stakeholders in the government, academia and companies in the Brainport region: the Urban Development Initiative - UDI. It aims to provide integrated and innovative answers to complex urban issues in the region. Initiatives like digital twinning can then be developed more efficiently, and then scaled up (Brainport Eindhoven, 2023).

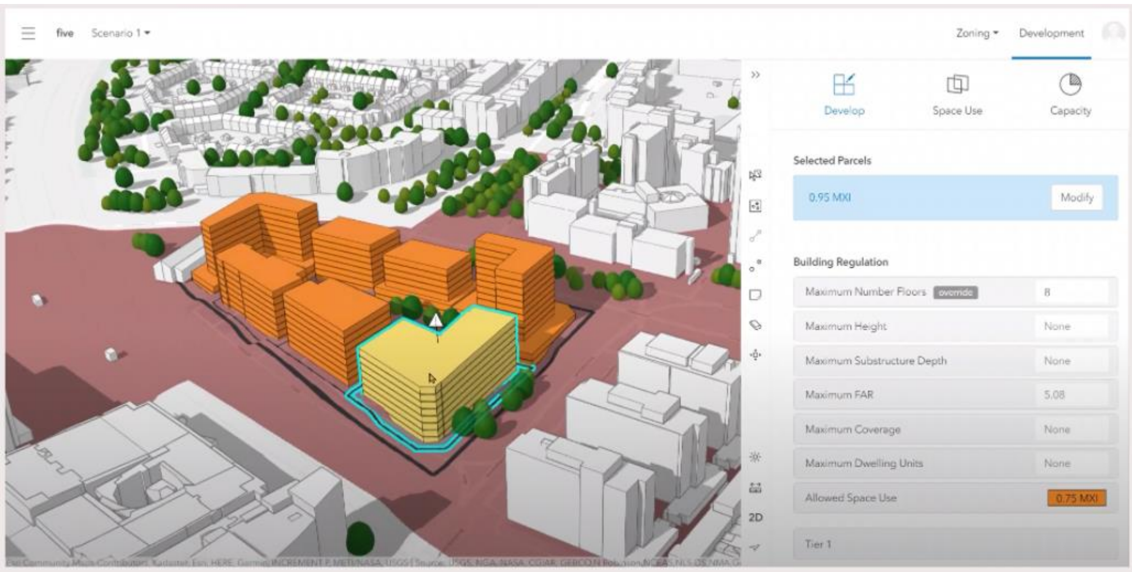


Fig. 4-5: Eindhoven 3D city model.

In the north of the Netherlands, Groningen also adopted the digital twin approach while working together on a digital 3D model of the city, both above and below ground: the 3D Digital City. It is seen as the next step to optimize the entire construction chain. Until recently, the departments were separately working on the issue of how the transition to 3D should take place. At the end of 2018, Geo&Data Department initiated discussions with urban engineers and urban development to find out what the thoughts are about working in 3D. During these discussions it became clear that all three departments would like to tackle a transition from 2D to 3D in an integrated manner. During joint meetings, input was provided for a vision document.

Fig. 4-6: Groningen 3D Digital City.

Table 4-3: Other digital twin initiatives at municipal-level.

Municipalities	Main Use Case	Source
The Hague	Monitoring pedestrian and biker flows	OTAR (2021)
Almere	Improving building permit processes	GemeentenNL (2023)
Nijmegen	Planning of big events	ANS (2022)
Zwolle	Simulating heat stress and rise of water levels	Gemeente Zwolle (2023)
Den Bosch	Crowd management	Argaleo (2019)

The model aims to provide: better communication with residents, citizen participation; faster and more informed decision-making; more insight into the design phase in the construction process; more insight and therefore less failure costs in the realization phase in the construction process; meeting expectations inside and outside the organization; insight and visualization of soil structure and underground objects in relation to the surface; better alignment with the Environment Act; better alignment with digitization and innovation. Other municipalities are also developing their digital twin initiatives. A brief description of these projects is presented in the Table 4-3 above.

Not only cities, but large pieces of infrastructure have also been the object of digital twinning. One example is the Lekdijk, a dike that protects one of the most populated areas in the Netherlands from the Lek river, a part of the Rhine-Meuse (Rijn-Maas) delta. If the northern Lek dike is breached, the economic and human damage would be enormous. A large part of the Randstad, the main Dutch metropolitan region, would be flooded. Climate change, among other things, could significantly increase the water levels at peak times in the coming decades. A large part of the Lekdijk between Amerongen and Schoonhoven is not designed for this and no longer meets the safety requirements. The Lekdijk must therefore be reinforced over a distance of more than 50 kilometers. This is the objective of the Sterk Lekdijk project (Geodan, 2023a).

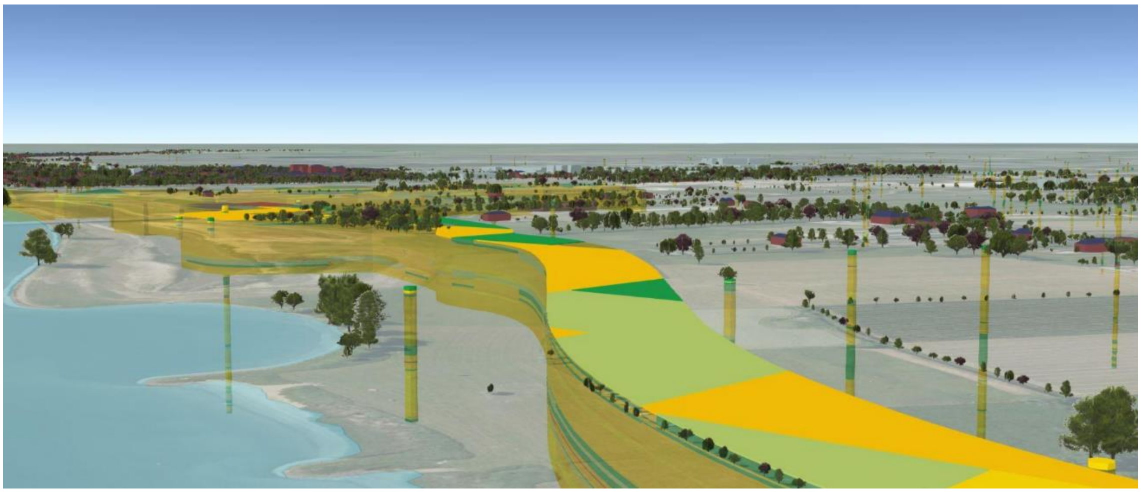


Fig. 4-7: Lekdijk Digital Twin.

The Lekdijk Digital Twin was developed by the company Geodan for the water board De Stichtse Rijnlanden, a public entity responsible for managing the water infrastructure in part of the delta region. Beyond soil data visualization, it aims to also show future scenarios, now that geometries and other relevant building information can be imported from a BIM model to a GIS environment. This way it is possible to get an idea of planned measures in advance. Experience technology also makes it possible to virtually step into the digital twin to explore and experience the consequences of chosen measures in advance. This helps to inform stakeholders and to create support. Future scenarios can already be evaluated in 3D during the design phase and adjusted if necessary. Table 4-4 below presents the intended added value of the digital twin (Geodan, 2023a).

Table 4-4: Added value of Lekdijk Digital Twin. Adapted from Geodan (2023).

Benefits	Practical examples
Planning efficient soil research	Input, manage and reuse Cone Penetration Tests (CPT) and lithological input (GeoTOP)
Safety analysis of dike sections	Modeling lithology; identifying groundwater bodies; mapping the presence of anthropogenic constructions; use of existing stochastic subsurface model
Information for tenders	Output lithology (construction subsurface); export geohydrology; export anthropogenic constructions
Using information in the design process	Output lithology; limit risks based on known challenges
Risk Management	Modeling lithology; identifying the presence of anthropogenic objects
Transparency and participation	Visualization surface; visualization of data from various sources and their interrelations; visualization of future dike design in context
Information transfer between phases	3D data room facilitates optimal information exchange

Public digital twin initiatives are not only laid out in the land, *Digitwin Noordzee* wants to make spatial plans for the North Sea and their effects on the environment more transparent. The ambition is to create a state-of-the-art supporting tool for policymakers, stakeholders, scientists and citizens that facilitates decision-making about the North Sea. As a digital replica of the North Sea, it also includes various calculation models. Because a lot of nature is under water and it is difficult for people to imagine how busy the North Sea is, a virtual reality module has also been created (Geonovum, 2022).

Fig. 4-8: Digitwin Noordzee interface. Source: DigiShape (2023).

4.3.2 Private Initiatives

In the private sector, some digital twin initiatives aim to reconstitute some aspects of the whole Dutch territory. By translating publicly available data about the built environment into a user-friendly viewer, companies have invested in creating national digital twins.

The platform *Nederland in 3D*, for example, offers a comprehensive 3D digital twin solution based on open standards and open integration. It is a result of a collaborative effort between companies with different expertise, like Future Insight, which also distributes VirtualCitySystems products in the Netherlands(Nederland in 3D, 2023). The digital twin *3DNL*, by Cyclomedia, includes features such as mesh measurements (distance, height, volume), asset management, shadow analysis, solar capacity calculations and building cross-sections (Hexagon, 2021).

Fig. 4-9: Cyclomedia's 3DNL. Source: Hexagon (2021).

Built on top of the GeodanMaps platform, Geodan is building the 3D Maquette, a replica of the Dutch built environment, covering the whole territory and offering stakeholders the following services: make better spatial decisions using analytics in one insightful map image; combine data and information that are relevant to a theme, also in combination with their own data; linkable to thousands of spatial data from our national registers via open standards, from local data to national scale; in addition to 3D visualization, also suitable for dynamic display of sensors and simulations; a usage-based subscription provides access to the foundation of digital twin data and tooling for your entire organization (Geodan, 2023b).

Fig. 4-10: Geodan 3D Maquette Viewer. Source: Geodan (2023a).

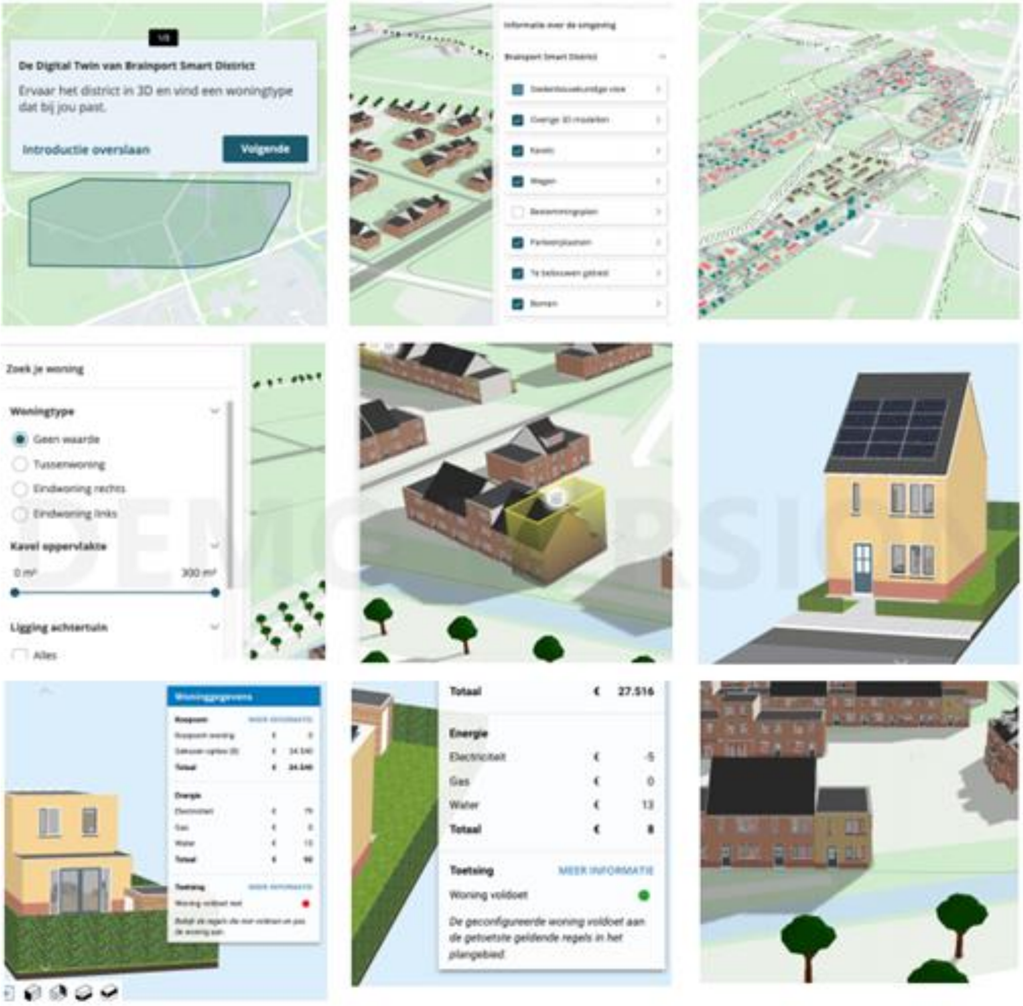


Fig. 4-11: Steps in the BSD Digital Twin interface. Source: Geonovum (2021b).

In 2020, a team from Brainport Smart District, the Municipality of Helmond, the Province of Noord-Brabant, Eindhoven University of Technology, WoonConnect and Geodan started a digital twin project, supported by the Digital Government Innovation Budget. The first step was to draw up a customer journey to realize the housing needs of future residents. The insights from the participation process and sessions with all stakeholders were then incorporated into the UX design of the digital twin. The final product is a proof-of-concept enabling future residents to choose a site and configure their home (Geonovum, 2021b).

The company Argaleo developed in 2019 the web-based platform *Digitwin*, aiming to provide data-driven social insights for local governments. Current customers' use cases are: Data-driven policy-making, mobility analysis, housing analysis, environmental monitoring, crowd management, operational traffic planning, geo-marketing, smart infrastructure planning. The platform can also be configured modularly and can be used with clients' own data as well as with enriched data packages. The client always remains the owner of their own datasets (Argaleo, 2023).

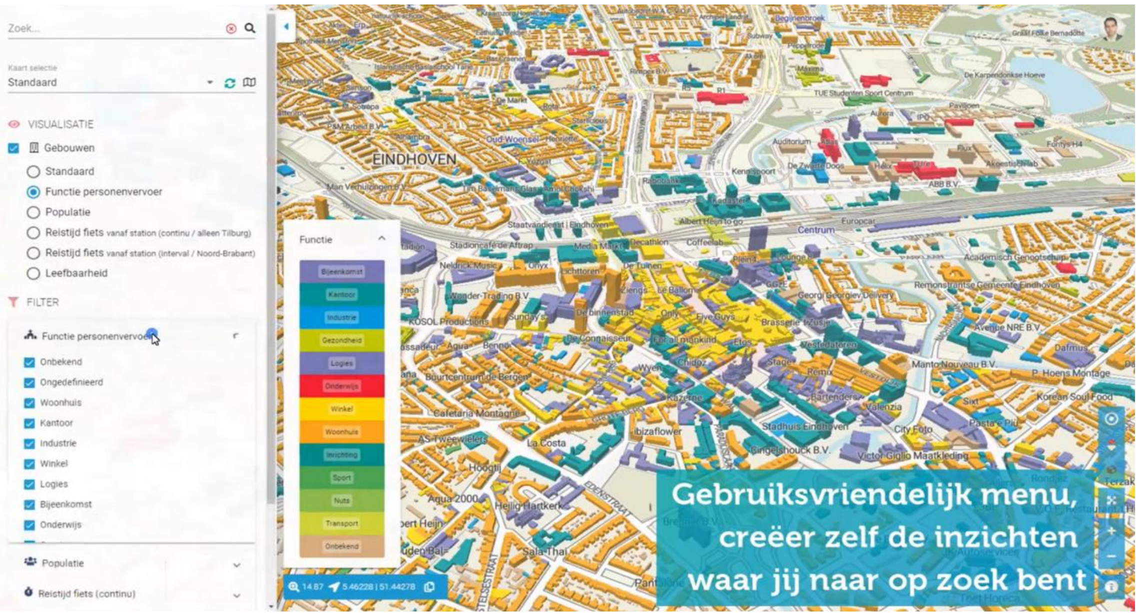


Fig. 4-12: Digitwin Interface. Source: Argaleo (2023).

In development since 2005, Tygron Geodesign Platform provides an advanced high-performance computing solution to solve urban challenges. The platform offers the digital infrastructure to support issues related to spatial planning, combining (geo)data, models and applications. It helps organizations to make quick and informed decisions and solve the world's biggest challenges, such as floods, droughts, heat waves, energy, housing, infrastructure, quality of life and the economy (Tygron, 2023).

Fig. 4-13: Tygron water simulation module. Source: (Tygron, 2019).

The most important logistics hotspots in the Netherlands, the Port of Rotterdam and Schiphol International Airport have also invested in developing digital twins to improve their operations. The Port's Digital Twin has been developed to make the digital strategy for its own organization tangible and visual. The aim is to be the first port that can receive autonomously sailing ships, but above all to keep the port leading in terms of efficiency and possibilities for the port's customers (CIO, 2019). In Schiphol, a common data environment collects and processes data from remote sensors at the airport that are used in predictive maintenance. More than a 3D building model, the airport's digital asset twin is able to run simulations on potential operational failures throughout the entire complex, saving financial resources and time (ESRI, 2019).

4.4 Comparative Analysis Results

According to the interviews guided by the Digital Twin Assessment Template, it was possible to have a deeper understanding from the projects listed on Table 4-2. This section aims to present results and analysis regarding the maturity level, resources invested, development time, technology adopted and features of the platforms.

4.4.1 City Data

Understanding the city context is important to frame and compare different initiatives. Table 4-5 below presents the main economic and demographic data regarding the cities which had officials interviewed during this research. It encompasses mostly the biggest cities in the Netherlands.

Table 4-5 also reveals that all of the assessed cities already have an operating open data portal, enabling downloads. Almost all of them (4 out of 5) also have at least one 3D dataset available for download. It means that Dutch cities are already mature and have internal capacity in terms of data management and services before they undertake digital twin initiatives. Many of them (3 out of 5) also have a ruling smart city strategy, which is capable of framing the Digital Twin project in a broader context of urban innovation.

Table 4-5: Consolidated city data.

	Amsterdam	Rotterdam	Utrecht	Eindhoven	Groningen
City population in 2021 (CBS)	873.338	651.631	359.370	235.691	233.273
Average Annual Income per capita in 2019 (AlleCijfers.Nl)	€31.200	€25.100	€29.200	€27.500	€24.700
Smart City Strategy	Yes, approved/ ruling. Agenda Digitale Stad	Yes, approved/ ruling. Digitale Stad.	Yes, approved/ ruling. Utrecht Digitale Stad	Not anymore. Eindhoven Smart City Program.	Not yet, it is in the roadmap
Open data portal/ 3D data available for download	Data Amsterdam, yes 3D data in 3D Amsterdam	Dataplatform Rotterdam, yes 3D data in 3D Rotterdam	Dataplatform Utrecht, yes 3D data in 3D Utrecht.	Eindhoven OpenData yes, GML dataset	Groningen Open Data. No 3D data.

4.4.2 Administrative Conditions

This section presents the main findings regarding Administrative Conditions section of the Digital Twin Assessment Template. Most digital twins were found to be operational (7 out of 10), but they are constantly being perfectioned and gaining new functionalities. Most digital twins are multi-purpose platforms (6 out of 10). Those who are still focused on one topic, are also planning to encompass other topics in the near future.

The staff in the projects range between 3 and 20 full-time workers. Most of them have around 10 people working in the digital twin initiative. Non-technical professionals, such as lawyers, notaries, communication experts, are usually engaged in the digital twin projects to meet specific needs. It does not mean necessarily that there is a multidisciplinary collaboration effort.

Almost all initiatives (8 out of 10) started from 2018 on, based on previous GIS/data platforms already existing in the municipalities. Half of the digital twin projects had a budget from € 400,000 to 600,000 in the last 2 years to get to the current development stage (5 out of 10). Some private solutions are more developed and have more resources invested over time, reaching € 30,000,000. Most digital twins have funding secured for further development and operation in the next few years (8 out of 10).

Regarding their management, municipal digital twins tend to have a more collective management model, even if often not institutionalized. Private companies have a more technical-oriented approach, designed to solve issues arising from the operation of the digital twin.

In terms of maturity level, most digital twins are between a 3D visualization platform and a data analysis platform (7 out of 10). Private platforms, developed and held by companies, are usually more advanced when it comes to incorporating real time data. Fig. 4-14 below shows how the initiatives are distributed into the different levels, considering a framework adapted from Griffith & Truelove (2021).

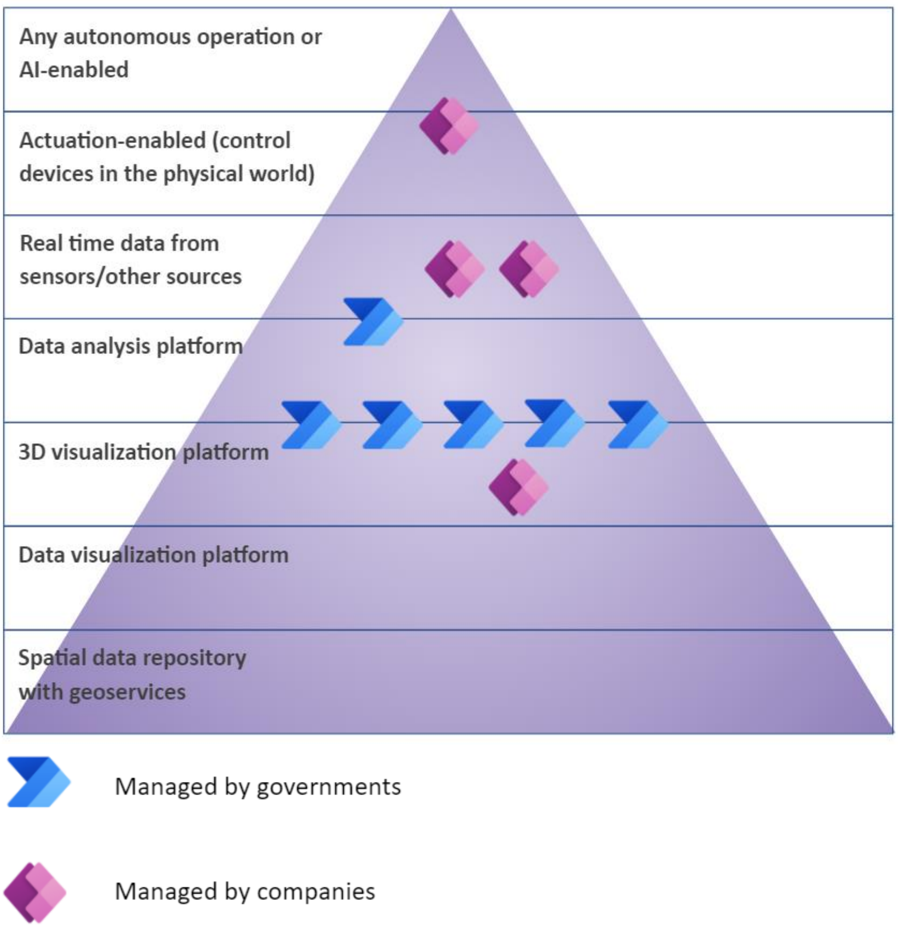


Fig. 4-14: Maturity level of digital twins in the Netherlands.

4.4.3 Entities and their role in the Digital Twin Ecosystem

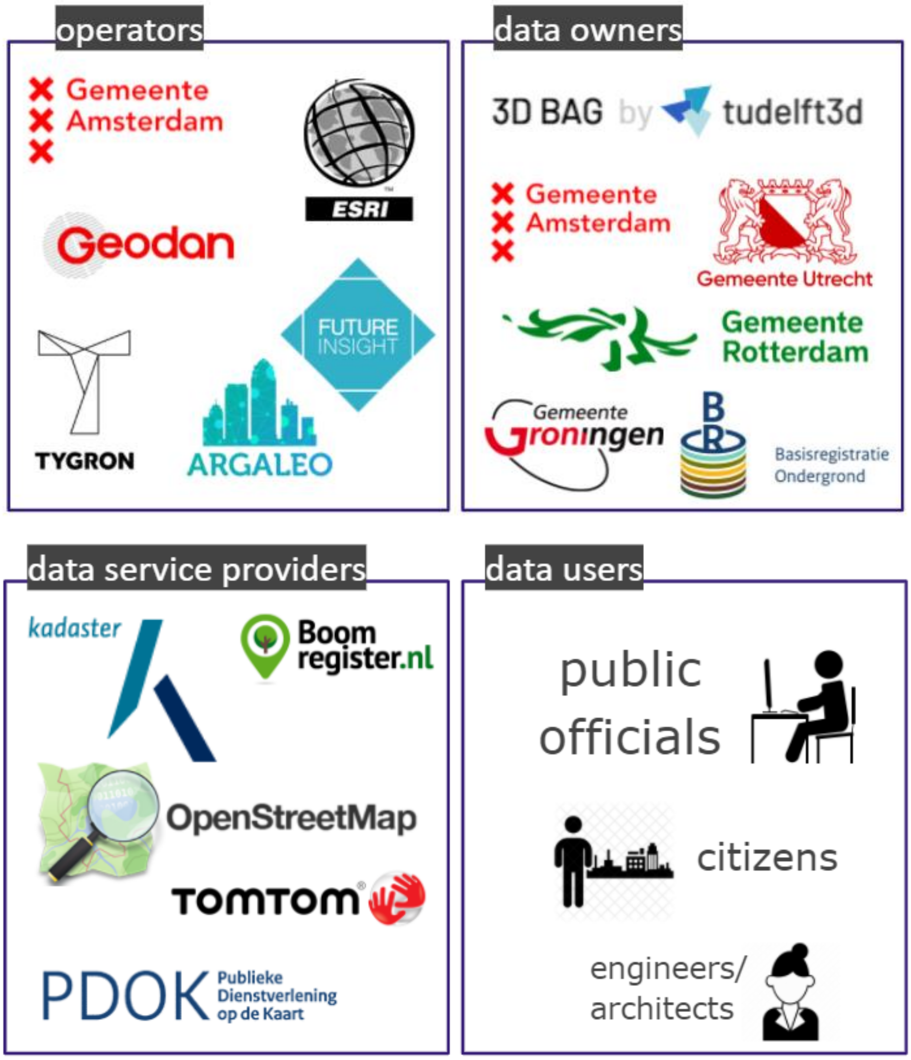


Fig. 4-15: Overview of the Digital Twin Ecosystem in the Netherlands.

According to Griffith & Truelove (2021), DT ecosystems can be understood by the interaction of some types of stakeholders. These types are listed below and Fig. 4-15 presents what this ecosystem would look like in the Netherlands based on the interviews.

- *DT platform / application operator*: responsible for developing, operating and maintaining a digital twin platform or application. In the case of Dutch municipalities, most of them have a third company as operator.

- *DT data custodians/owners*: collects, generates, maintains data for the purpose of carrying out their functions. Mainly organizations offering publicly available data and in some cases the city also acts as a data owner, when using its own dataset in the digital twin.
- *DT data service providers*: provides digital twin data services to data custodians or digital twin platform operators. In the Netherlands, Kadaster, PDOK and OpenStreetMap were considered to be the main data service providers.
- *DT data users*: end-user of the digital twin platform, which are able to draw insights and support decision-making. The research shows that they are mainly municipal officers working in urban and environmental planning, but also other departments in the municipality.

4.4.4 Quadruple Helix Engagement

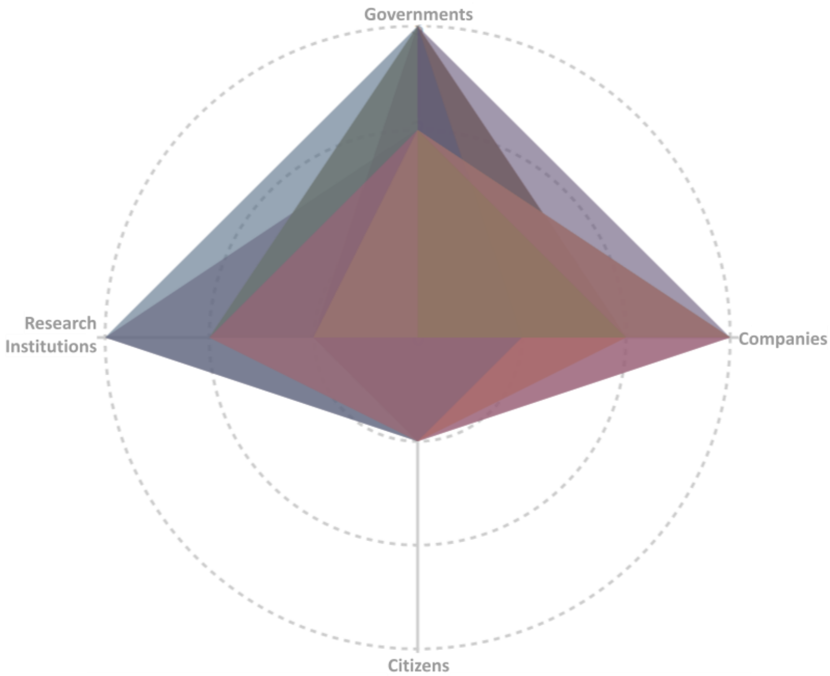


Fig. 4-16: Consolidated Stakeholder Engagement Diagram.

According to Schütz et al. (2019), the Quadruple Helix Model of innovation recognizes four major actors in the innovation system: science, policy, industry, and society. In keeping with this model, more and more governments are prioritizing greater public involvement in innovation processes. In this study, the projects were assessed in their stakeholder engagement according to this model. Fig. 4-16 presents a diagram of stakeholder engagement in the digital twin environment.

As seen on Table 4-6, among the studied projects the government is always engaged in the design phase, always has access to the digital twin and is very often involved in the management and operation. All the projects have or had partnerships with Dutch universities. Universities and research institutions, when involved in the project, are usually engaged in the design phase, management and operation. The same happens when a company is involved in the digital twin development. The assessment revealed that citizens are not usually engaged in the design phase. They also usually don't have access to the platform (only in 4 out of 10) and were not found to be engaged in the operation and management of the digital twin.

Table 4-6: Stakeholder Engagement Assessment.

Digital Twin Projects		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Engagement in DT Planning/ Design Phase (E1)	Government	■	■	■	■	■	■	■	■	■	■
	Companies	■	■	■	■	■	■		■	■	■
	Citizens	*									
	University/ Research Institutions	■	■		■	■				■	
Access to DT (E2)	Government	■	■	■	■	■	■	■	■	■	■
	Companies	■	■	■			■		■	■	■
	Citizens		■	■		■				■	
	University/ Research Institutions	■	■	■	■	■			■	■	
Engagement in DT Operation/ Management (E3)	Government		■	■	■	■	■	■			
	Companies	■			■		■		■	■	■
	Citizens										
	University/ Research Institutions	■				■					

* group of prospective new residents

4.4.5 Adopted Technologies

Regarding the technology chosen for the viewer, Cesium was the most used, followed by solutions based on Mapbox, game engines (Unity and JMonkey) and ESRI solutions (ArcGIS PRO). Avoiding vendor lock-in was a concern present in all interviews. Most initiatives do not depend on commercial software, but some use ESRI commercial solutions. The Level of Detail - LOD of buildings range between 2 and 3. Almost all digital twins have cloud-based data storage (mostly AWS and Azure), or are migrating to this type of data storage. Database solutions are diverse (PostgreSQL, Oracle Spatial, Unity Assets, MongoDB, 3DCityDB).

Most digital twins don't offer an **API** (7 out of 10), only two of the platforms developed by companies and one of the municipalities have an operating API. Most interviewees mentioned that it was on their road map for the next few years. None of the digital twins have a dedicated middleware for IoT, like Kaa, Sofia, Fiware. It reveals that real time sensor data is still being incorporated into these digital twin solutions. Practically all digital twins addressed interoperability by using only open-standard data formats. Almost all digital twins don't handle or own any kind of personal data. Only one of the platforms process private information, but the company does not own it, but the municipality.

Table 4-7 below presents the input and output data formats and the Digital Twin features of the assessed projects. The most popular feature in digital twins is the application of queries in one dataset, followed by the ability to export data (tables and 3D) and the application of queries in multiple dataset at the same time. The most common used data formats (in order) were:

- input: tables, BIM files and GIS files, 3D and CAD files and CityGML.
- output: tables, Cesium 3D tiles, BIM and GIS files.

Table 4-7: Input/output data formats and digital twin features.

Digital Twin Projects		**01**	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**
Input data formats	CityGML			●	●	●	●	●	●		●
	CityJson			●	●	●			●		●
	GIS shapefiles (.shp, sdf, .gdb, .geojson…)	●	●			●	●	●	●	●	●
	CAD files (.dwg, .fbx...)	●	●	●		●		●	●		
	3D files (.skp, .3dm..)		●	●	●	●	●	●	●		
	Cesium 3D tiles	●			●	●		●			●
	BIM files (.ifc, .rvt…)	●	●		●	●		●	●		●
	Tables (.xlsx, .csv)	●	●	●	●	●		●	●		●
Output data formats	CityGML				●	●		●			●
	CityJson				●	●		●			●
	GIS shapefiles (.shp, sdf, .gdb, .geojson…)	●	●			●		●		●	
	CAD files (.dwg, .fbx...)	●		●		●		●			
	3D files (.skp, .3dm..)			●	●	●		●			
	Cesium 3D tiles	●			●	●		●			●
	BIM files (.ifc, .rvt…)	●			●	●		●			●
	Tables (.xlsx, .csv)	●			●	●		●	●	●	
DT Features	Dashboards		●				●		●	●	
	Displays real time data				●		●		●	●	●
	Interactivity (with widgets)	●	●	●		●	●	●	●	●	●
	Export data		●		●	●		●	●	●	●
	Export 3D data		●	●	●	●		●		●	●
	Enable data downloads to the public			●	●						●
	Apply queries in one dataset	●	●	●	●		●	●	●	●	●
	Apply combined queries in multiple datasets at a time	●	●				●	●	●	●	●

4.4.6 Project Development Process

Concerning the project development process, half of the digital twins started with a vision and principles guiding the process, mainly municipalities. The other half started from a use case, mainly the platforms developed as commercial solutions by companies. There is usually no framework for a full digital twin implementation.

Only one municipality mentioned that the overall architecture was under development.

While half of the procurement processes necessary for the digital twin development relied on traditional procedures, the other half depended on alternative procedures due to the innovative character of the product. It happens because the business and technology environment plays an important role in the project development.

4.4.7 Impact and Challenges

Most digital twins (6 out of 10) already promoted changes in at least one organizational process so far, such as the preparation of 3D base models for new urban design projects and consultation of new information before decision-making. None of the projects included a quantitative measure of the added value of the digital twin yet, but all reported a qualitative improvement of processes. As with every piece of infrastructure, it is challenging to translate digital twin benefits into financial returns, but it should be the object of further research.

The main challenges facing digital twin initiatives according to the interviews are:

- data collection: in many projects working with primary data (soil conditions, building features, etc), it is challenging to collect data in a timely and comprehensive manner at a reasonable cost. This data is necessary in many cases in order to keep the extent to which the digital twin replicates reality.
- organizational change: the digital twin is a new digital infrastructure and in order to be useful it needs to be integrated to existing organizational procedures. It requires a new work culture or changes in processes.
- finding the right use cases: in some projects, there is no meaningful technical challenge. The main challenge is then how to apply the existing solutions to emerging needs in city management.
- procurement: since digital twin solutions are a new field, it is difficult for municipalities to describe their platform needs in clear documents. There are also less services offered and a difficulty to compare objectively different solutions.

- interoperability: while most of the municipalities are concerned about using interoperable data formats, it is still not clear how interoperable are the different digital twin solutions.

The next steps are of the assessed projects are: securing more funding for further development, data collection efforts, extending GIS functionalities, creating a digital urban community, combining different 3D models, including sensor data, making the digital twin open for everyone, perfectioning calculations and simulations, keeping track of historical data and changes in the model.

4.5 Conclusions

In total, this study showed that 37,5% of the Dutch municipalities with over 100.000 inhabitants (12 out of 32) are working on digital twin projects. The long tradition in keeping track of the territory translated in a robust cadaster fostered the implementation of these initiatives. They usually aim to: (a) bring together the legal, administrative and physical reality; improving communication, residents and project initiators; (b) more insight into the design phase with more data-based scenario creation; (c) preparation for the new environmental ordinance, the *Omgevingswet*.

It can be concluded from this assessment that the Netherlands has a vibrant digital twin ecosystem. Many pioneer initiatives undertaken in different cities and organizations have been creating a market for new service providers. Avoidance of vendor lock-in and adherence to standards are a solid consensus among the different projects and Geonovum's national regulation initiative appears to be taking advantage of this moment to propose more specific guidelines towards interoperability.

The closer look to some of these projects revealed the above mentioned strong points, but also some shortfalls of the initiatives. While most projects have citizens' quality of life as their end goal, it is not clear to what extent they have been benefitting from the digital twins so far. Very often use cases are still being searched after technical development has already taken place. It is also clear that citizens have not been integrated into the design and implementation of digital twins, even if at a conceptual level. The next chapter brings a strategic methodology to implement digital twins at the city-level, aiming to address the identified issues, also considering good practices in the Netherlands and around the world.

4.6 References

ANS. (2022, February 11). *Digitale tweeling van Nijmegen belooft veiligere evenementen*. https://ans-online.nl/nieuws/digitale-tweeling-van-nijmegen-belooft-veiligere-evenementen/

Argaleo. (2019, October 21). *Bezoek Argaleo op Den Bosch Dataweek 2019*. https://www.argaleo.com/2019/10/21/bezoek-argaleo-op-den-bosch-dataweek-2019/

Argaleo. (2023). *Digital twin van jouw stad*. https://www.argaleo.com/digitwin/

Brainport Eindhoven. (2023). *Urban Development Initiative*. https://brainporteindhoven.com/udi/en/

BZK. (2023a). *Basisregistratie Ondergrond*. Ministerie van Binnenlandse Zaken En Koninkrijksrelaties. https://basisregistratieondergrond.nl/inhoud-bro/bro/

BZK. (2023b). *Executive summary of the NOVI*. https://novistukken.nl/english/default.aspx

CIO. (2019, June 24). *Port of Rotterdam – Met de Digital Twin de slimste haven*. https://www.cio-platform.nl/k/nl/n626/news/view/8057/6753/port-of-rotterdam-met-de-digital-twin-de-slimste-haven.html

DigiShape. (2023). *DigiTwin*. https://digitwin.maris.nl/

ESRI. (2019, October). *Digital twin helps airport optimize operations*. https://www.esri.com/about/newsroom/wp-content/uploads/2019/10/airport.pdf

ESRI. (2021). *Stedenbouw 2.0: Digital Twin voor Complexe Stedelijke Vraagstukken*. https://magazine.esri.nl/esri-magazine-1-2021/gemeente-eindhoven

Gemeente Amsterdam. (2023). *3D Amsterdam*. https://github.com/Amsterdam/3DAmsterdam

Gemeente Rotterdam. (2023). *Digitale Stad*. https://www.rotterdam.nl/digitale-stad

Gemeente Zwolle. (2023). *Veelgestelde vragen Digitale Tweelingstad Zwolle*. https://www.zwolle.nl/veelgestelde-vragen-digitale-tweelingstad-zwolle

GemeentenNL. (2023). *John Vreegenoor (Gemeente Almere): "Digital Twin brengt 3 werelden samen."* https://www.gemeentennl.nl/digitaal/john-vreegenoor-gemeente-almere-digital-twin-brengt-3-werelden-samen/

Geodan. (2023a). *Research Maquette Demo*. https://maps.beta.geodan.nl/maquette-dev/

Geodan. (2023b). *Nog beter beschermd tegen overstromingen*. https://www.geodan.nl/cases/een-stevig-fundament-voor-een-sterke-lekdijk/

Geonovum. (2021a). *Investeringsvoorstel Nationale Tweeling voor de Fysieke Leefomgeving*. https://www.geonovum.nl/uploads/documents/DTFL-Investeringsvoorstel-Compleet-v14.pdf

Geonovum. (2021b, August 31). *Brainport Smart District Helmond*. https://www.wijsmetlocatie.nl/artikelen/brainport-smart-district-helmond

Geonovum. (2022, January 6). *Digitale Tweeling Noordzee*. https://www.wijsmetlocatie.nl/artikelen/digitwin-noordzee

Griffith, C., & Truelove, M. (2021). *Framework for Spatially Enabled Digital Twins: Information Paper*. https://www.anzlic.gov.au/sites/default/files/files/Data61%20Digital%20Twin%20Framework%20Information%20Paper%20-%20February%202021.pdf

Hexagon. (2021, April 29). *Hexagon's HxDR to host 3DNL, Cyclomedia's Digital Twin of the Netherlands*. https://leica-geosystems.com/about-us/news-room/news-overview/2021/04/cyclomedias-digital-twin-of-the-netherlands

IBR. (2023). *Omgevingswet*. https://www.ibr.nl/wiki/omgevingswet/

Interprovinciaal Overleg. (2023). *Inhoud van de Omgevingswet*. https://iplo.nl/regelgeving/omgevingswet/inhoud/?_ga=2.261525261.1628263793.1681133663-1438956483.1652451241&_gl=1*nvwgqs*_ga*MTQzODk1NjQ4My4xNjUyNDUxMjQx*_ga_MNGT91YQGE*MTY4MTEzMzY2Mi4xLjEuMTY4MTEzMzc3MC4wLjAuMA..

Jacobides, M. G., Cennamo, C., & Gawer, A. (2018). Towards a theory of ecosystems. *Strategic Management Journal*, *39*(8). https://doi.org/10.1002/smj.2904

Kadaster. (2023a). *Basisregistraties*. https://www.kadaster.nl/zakelijk/registraties/basisregistraties

Kadaster. (2023b). *Geschiedenis van het Kadaster*. https://www.kadaster.nl/over-ons/het-kadaster/geschiedenis

Nederland in 3D. (2023). *3D Digital Twin*. https://www.nederlandin3d.nl/

OTAR. (2021, March 3). *Den Haag: Digital Twin om piekdrukte voetgangers en fietsers te beheersen*. https://www.otar.nl/den-haag-digital-twin-om-piekdrukte-voetgangers-en-fietsers-te-beheersen/

Schütz, F., Heidingsfelder, M. L., & Schraudner, M. (2019). Co-shaping the Future in Quadruple Helix Innovation Systems: Uncovering Public Preferences toward Participatory Research and Innovation. *She Ji*, *5*(2). https://doi.org/10.1016/j.sheji.2019.04.002

Tygron. (2019, May 15). *De nieuwe watermodule van het Tygron Platform*. https://www.tygron.com/blog/2019/05/15/de-nieuwe-watermodule-van-het-tygron-platform/

Tygron. (2023). *Blogs - Tygron Platform*. https://www.tygron.com/blogs/

5 Strategic Methodology of Digital Twin Implementation at the City Level

5.1 Introduction

This chapter elaborates on a proposed methodology for digital twin implementation composed by a comprehensive set of guidelines and steps designed to facilitate the implementation of digital twins within the context of municipal governments, specifically in support of decision-making processes related to spatial planning. As digital twins are innovative solutions, their implementation may necessitate disruptive organizational changes, as well as iterative prototyping and testing.

The explanation of steps proposed in this methodology aims to cater to a diverse range of target groups, each of whom may derive distinct benefits from the content, as elaborated below:

a) *Elected officials or high-level government managers*: to gain insights into the resources and decisions required to facilitate the development and implementation of urban digital twins in their respective domains.

b) *Mid-level government managers*: to acquire an in-depth understanding of the necessary activities involved in implementing digital twins, enabling them to effectively delegate tasks to appropriate team members.

c) *Civil servants*: to follow the suggested steps and best practices for implementing digital twins, while gaining an overview of how their tasks contribute to the project's overall success.

d) *Citizens/residents*: to comprehend the various implementation steps and their roles in shaping government digital tools, fostering trust in government innovation, and actively participating in the decision-making process.

e) *Managers and business developers in companies*: to adapt and propose context-specific steps to assist with implementation as consultants. Develop digital tools for governments while actively involving stakeholders in the process.

f) *Software developers in companies or government*: to understand how their tasks relate to the project's overall strategy and the stakeholder engagement process, ensuring their contributions align with the broader objectives.

The process of implementation of digital twins is deeply influenced by the project financing. As innovative endeavors, these projects can be initiated in various financing contexts, including:

a) *Research grants*: Foundations, international organizations (e.g., the European Union), and national governments often provide funding for research projects in areas such as digital government, urban management, community engagement, and sustainability. In these cases, the expected outcome is the creation of new knowledge and advancements in technology, allowing for greater risk-taking in testing novel methods. Universities and other research institutions frequently lead or partner in these initiatives.

b) *Government grants*: Some national governments implement policy by making funds available for projects proposed by municipalities. These initiatives typically require a well-structured and feasible project plan that directly aligns with the high-level goals of the policy.

c) *Municipal budget*: In certain municipalities, proposals are developed at the technical level and submitted for approval by the mayor or city council to obtain necessary funding. These proposals must be sound, feasible, and directly address elected officials' priorities.

d) *Assignment from mayor or city council*: Some elected officials recognize the potential of digitalization and translate this into general guidelines or programs within the municipal government (e.g., Digital City Program or Smart City Strategy). In these cases, civil servants or managers must structure initiatives to achieve these goals within specified budgets and time frames.

e) *Motivated by partners*: Occasionally, universities, companies, autonomous public administration entities (e.g., water boards, public utility companies), or civil society organizations secure funding or allocate their own resources to initiate digital innovation projects. In such instances, the initiative tends to address the priorities of the partner, leaving less room for adjustment to municipal priorities.

The abovementioned financing contexts significantly impacts the steps and methods of implementation. Fig. 5-1 below illustrates the relationship between the context and the extent of planning and design occurring within the municipality before the project's actual start. If the starting point lies towards the right of the arrow, more steps from this methodology will be followed (particularly in the planning phase) before securing funding. If it lies towards the left of the arrow, fewer steps would be followed before the initiative begins, with the possibility of trying different steps and comparing results to focus on answering research questions rather than delivering new products or services to the municipality. In the case of partner-motivated projects, the specific approach depends on the partners' needs and chosen strategy.

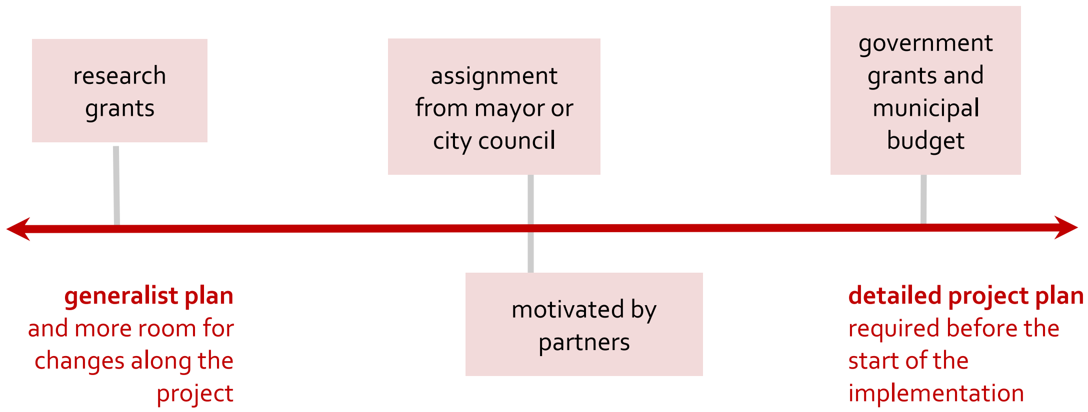


Fig. 5-1: Level of detail of project plans on different financing contexts.

5.2 Methodology Overview

This proposed methodology for implementing digital twins for cities consists of nine steps, organized into four major phases. Although these steps are intended to guide the prioritization of activities over time, it is common for steps and phases to overlap in most projects, due to issues such as workforce availability and political guidelines. The suggested milestones indicate the completion of each step, while high-level decisions mark the beginning of each phase. Based on the assessed initiatives, it is possible to estimate the implementation time between 3 and 4 years.

A) *Planning*: The planning phase involves laying the groundwork for the digital twin implementation.

- Step 1: Make a plan - Develop a comprehensive plan outlining the project's objectives, scope, timeline, and resource requirements.
- Step 2: Form a team - Assemble a multidisciplinary team of experts, including urban planners, data analysts, software developers, and other relevant stakeholders. Ensure that the team has the necessary skills and expertise to carry out the project.
- Step 3: System assessment - Conduct a thorough assessment of the existing urban systems and infrastructure to identify areas where digital twins can provide the most value. Consider the current challenges, inefficiencies, and opportunities for improvement.
- Step 4: Ideate solutions - Brainstorm potential digital twin solutions and applications, taking into consideration the findings from the system assessment. Prioritize solutions that align with the project's goals and available resources.

B) *Preparing*: The preparing phase focuses on gathering the necessary data and building capacity for the digital twin implementation.

- Step 5: Data and capacity assessment - Evaluate the available data and identify any gaps that need to be addressed. Assess the team's capacity to handle the data and develop the digital twin, determining any additional training or resources required.
- Step 6: Data collection - Collect the necessary data to support the development of the digital twin, addressing any identified gaps. Ensure the data is accurate, up-to-date, and adheres to relevant data privacy and security standards.

C) *Implementing:* The implementing phase involves the actual development and deployment of the digital twin.

- Step 7: Pilot digital twin - Develop a pilot version of the digital twin, focusing on a specific area or application identified during the planning phase. Test the pilot to evaluate its performance, gather feedback, and identify any issues that need to be addressed.
- Step 8: Digital twin development - Using the insights from the pilot, refine and expand the digital twin to cover the full scope of the project. Ensure that the digital twin is scalable and adaptable to accommodate future changes and updates.

D) *Operating*: The operating phase covers the ongoing management and maintenance of the digital twin.

- Step 9: Digital twin operation – Gradually launch the fully developed digital twin, ensuring that it is integrated with the relevant urban systems and processes. Continuously monitor its performance, update the data, and make adjustments as necessary to ensure its ongoing effectiveness in supporting decision-making and urban planning.

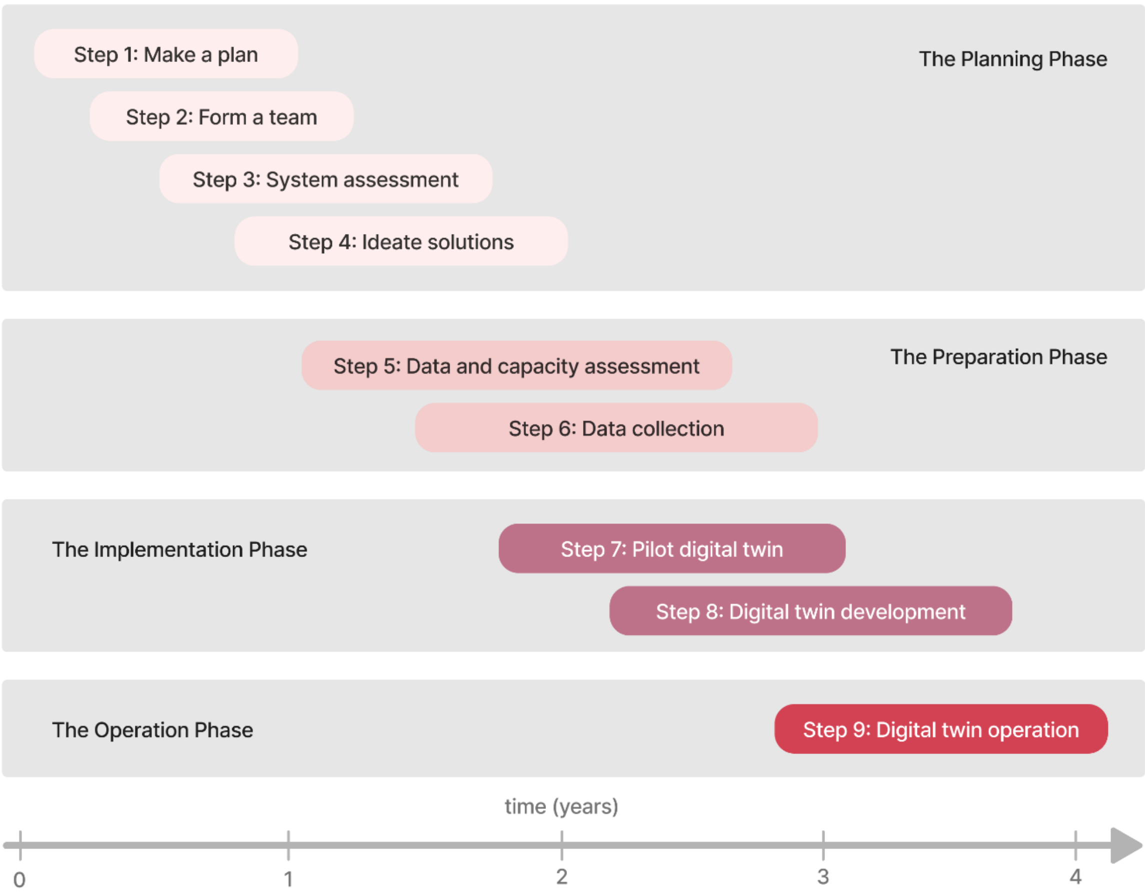


Fig. 5-2: Phases and steps of digital twin implementation over time.

5.3 The Planning Phase

5.3.1 Step 1: Make a Plan

It all starts with a plan. It is important to have a clear proposal of which problems the digital solution is expected to solve. As the strength of digital twins is enabling integral transdisciplinary solutions, it is important to engage collaborators from different departments and disciplines while writing up the plan. It will help get everyone involved, setting clear expectations in what will be accomplished, when and who. It is important to mention that in the development of innovative solutions, plans are intended only to guide the process, but not to limit it. Narrowing or broadening the scope and changes to the budget and team can happen along the way. Taking reasonable risks and testing solutions is crucial for a successful innovative solution. This step consists on the following activities:

- Identify some contemporary issues in the city and reflect how a digital twin could be a possible solution.
- Link the goal of this possible digital solution to current priorities of the administration.
- Preliminary assessment of main stakeholders. Hold meetings to identify requirements for the possible solutions.
- Elaborate proposal, outlining expected deliverables (following the steps of this guide can help when drafting a proposal).
- Check if the proposal meets international/regional/national standards (like the Gemini Principles) and if it promotes interoperability.
- List activities and estimate costs and time needed to implement them.
- If possible, establish success metrics for the project and undertake a risk assessment.
- Consolidate a project plan draft and discuss with other departments and stakeholders. In some cases the plan needs to be approved by city officials or a city council.
- <u>*Milestone*</u>*: Project Plan*

The approach to project setup can be influenced by the adopted project management methodology, so it is something that can be incorporated into the project plan. Following the Agile principles and a scrum framework can be a valuable strategy instead of traditional "waterfall" management, since the end product is often not known at the start of a digital twin project (Northeastern University, 2020). Thesing et al. (2021) propose a methodology to guide the decision between the two approaches based on 15 criteria subsumed under the following categories: scope, time, costs, organization context, and project-team characteristics. As shown in the Fig. 5-3 below, the Agile principles lead to shorter cycles of feedback, delivering value in the process. In large public initiatives such as a digital twin, it is expected to have some elements of both approaches, taking into account that moving to the next phase would require high-level decision.

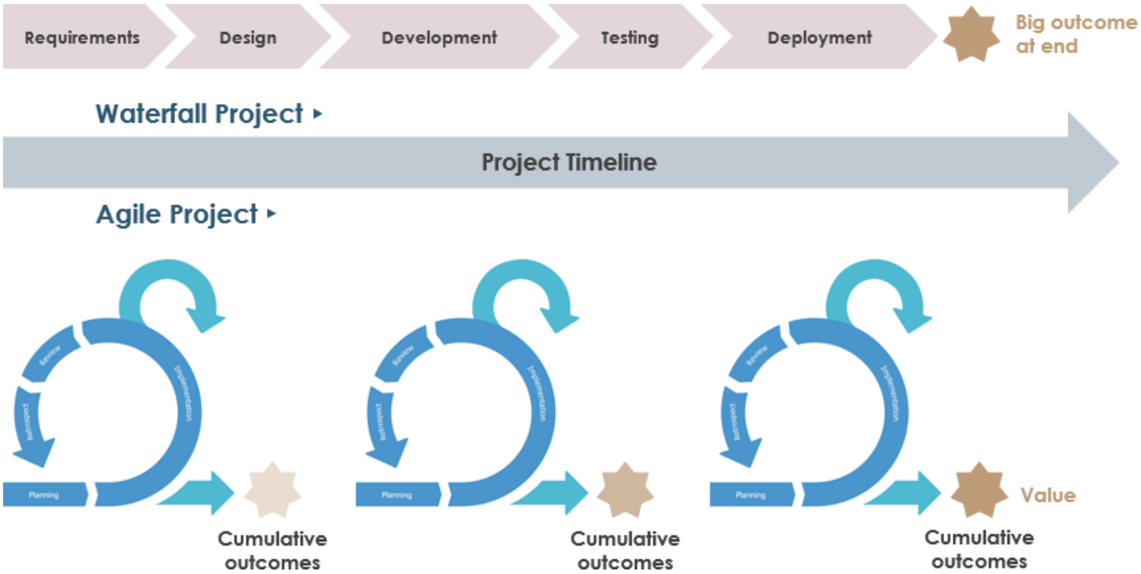


Fig. 5-3: Waterfall versus agile method. Source: Visual Paradigm (2023).

5.3.2 Step 2: Form a Team

Even with secured funding and political momentum, such initiative can only move forward with the required human resources. Implementing a digital twin project in a municipality requires knowledge from urban planning, service design, software development, project management, community engagement, among others. It means a multidisciplinary team is necessary and should work together as early as possible for a better outcome.

In most organizations, teams are set up by their training, like architects in the Architecture Department and engineers in the Engineering Department. This kind of set up works to perform repetitive tasks or develop products when the processes are well-defined. In the case of developing digital twins or other innovative urban solutions, it is important to consider the perspectives of professionals from different backgrounds. Multidisciplinary work environments are able to bring breakthroughs by combining a larger spectrum of knowledge.

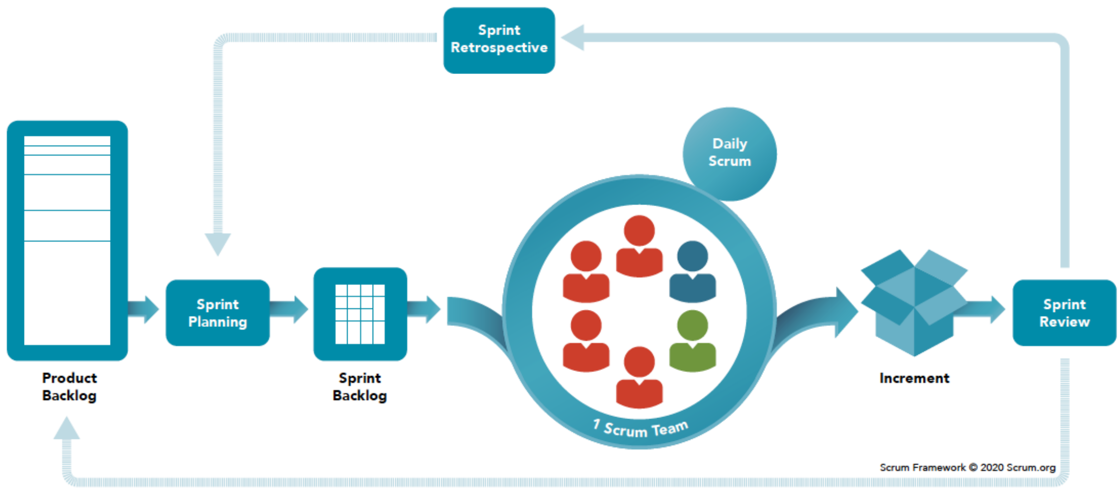


Fig. 5-4: Scrum framework. Source: (Scrum.org, 2023).

If the funding is still not secured for a full time team, collaborators from different disciplines can dedicate part of their working hours to implement the first steps and help secure the necessary funds. This team forming step consists on the following activities:

- Develop profile and expertise needed at this moment of project kick-off, e.g. a project manager, an urban planner, a data scientist, a software architect, a scrum master and a service designer.
- Identify people in the organization with training or knowledge in the required fields to assess the profiles and assist in the process of hiring and selection.
- While performing interviews, assess also the ability and willingness to work in groups, to listen and to be creative. Short assignments and group dynamics can be more insightful than only interviews.
- Bring diversity to the team not only in terms of expertise, but also gender, race, culture and so on. Having a heterogeneous team brings possible conflicts at an early stage of the project and makes it possible to address societal issues and bias from the beginning.

- Define a clear working method (e.g. based on the Agile Principles and the Scrum Framework) and create an innovation-friendly work environment.
- *<u>Milestone</u>: Team setup proposal, job postings and hiring.*

One example of multidisciplinary teams working on innovation projects are Bloomberg “i-teams”. They assist city mayors on tackling pressing challenges and delivering better results through creativity and innovative thinking, “Innovation teams are uniquely positioned to make big dents in tough problems. They gather and use data and look beyond their city limits to learn from other contexts. They are human-centered, tackling challenges by enlisting residents to help define problems and test solutions. They test ideas early to improve them quickly and remain focused on results. And, they are versatile, shouldering challenges across a broad array of city issues and bringing people together across departments to take them on.” (Bloomberg Philanthropies, 2023).

5.3.3 Step 3: System Assessment

Understanding the context of implementation is important in every project. In the case of government initiatives, the resources of the municipality must be optimized to address the most pressing issues or improve administrative efficiency and effectiveness of public policy. Cities are complex systems and it is important to dedicate time and effort to identify how technology can contribute to improve quality of life for all residents. The sub-steps below intend to create the initial capacity within the city government and perform a data-based and people-centered diagnosis of current problems:

- Identify and detail a pressing issue in the city (housing, climate change, crowd management, among others), by interviewing city officials, city council members, head of departments, residents and universities. Describe it as a system, decomposing into subsystems.
- Identify key stakeholders (people/organizations which can potentially benefit or be impacted by the project) and consolidate them in a stakeholder management plan, containing their name, role, position and contact information. Methodologies like a power-interest matrix

can help prioritize them and establish the guidelines for communication (frequency and type of communication). After documenting expectations, an action plan is laid out to ensure expectations are met.

- Describe public services and organizational roles around this pressing issue. Choose one or more processes. Preferably choose two processes that could mutually benefit from integration.
- Identify bottlenecks and opportunities for improvement with digitization through interviews and workshops.
- Present and validate results of the systemic assessment (organize an open event or publish online for feedback).
- *Milestone: Report of pressing issues, stakeholder management plan, systemic assessment report.*

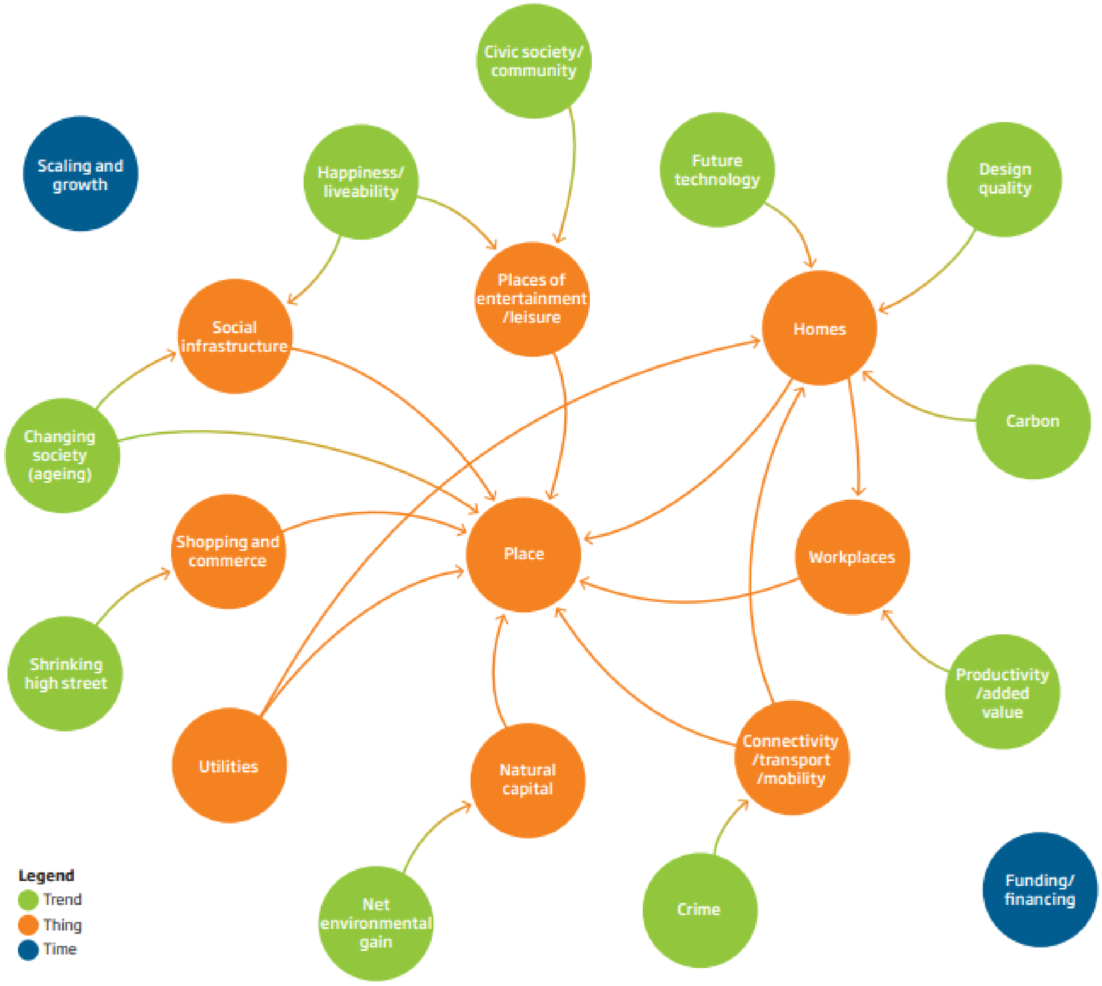


Fig. 5-5: System elements of sustainable living places. Source: Royal Academy of Engineering (2020)

The National Engineering Policy Centre (NEPC) led by Royal Academy of Engineering developed a systems map for housing, planning and infrastructure from a series of workshops with key stakeholders. It identified silos, lack of focus and conflicting priorities and interests within the current system. The decisions are often not evidence-based and lack crucial long-term and strategic thinking. For instance, poor connections generate car dependent places, leading to pollution, carbon emissions and other health issues (Royal Academy of Engineering, 2020). In other words: environment, mobility and public health are clearly interrelated, but the policies are still being discussed in silos. A better comprehension of the concerned systems can also leverage opportunities for a better approach to the problem.

5.3.4 Step 4: Ideate solutions

After understanding the complexity of the context, it is time to propose possible solutions. The implementation of digital twins and similar urban information systems require innovative solutions. Most times cities don’t have a standard solution to address the issues identified in the system assessment. Design thinking and co-creation methods can facilitate this creative process. In order to be successful, it is important to guarantee an innovation-friendly environment fostering principles like: an organizational structure that facilitates collaboration, a test-and-learn mindset and a clear strategy.

According to Innovate-D (2018), the required expertise for innovation can be categorized into three domains: (i) innovation process knowledge, which encompasses methodologies such as design thinking, lean start-up, and agile project management; (ii) framework knowledge, which includes tools like the business model canvas, value chain analysis, and customer journey mapping; (iii) facilitation knowledge, which covers techniques such as brainstorming, focus groups, root cause analysis, and the five whys approach.

A successful innovation strategy relies on maturity across six key capabilities, as outlined in Fig. 5-6. Firstly, a culture that embraces change, diversity, and the possibility of failure is essential, addressing issues such as "not invented here" and "not my problem." Secondly, employees must possess robust domain knowledge related to their core roles, be team players, and have diverse experiences. Thirdly, appropriate recognition and rewards based on roles should be implemented to incentivize innovation. Fourthly, a well-defined innovation process should be in place, outlining idea generation, evaluation, transformation, and implementation with proper stakeholder involvement and change management. Fifthly, frameworks should be utilized to structure ideas, provide a common language, and support communication. Lastly, effective two-way communication is crucial for promoting ideas, spreading the message associated with innovation activities, and receiving feedback from recipients throughout the entire innovation process.

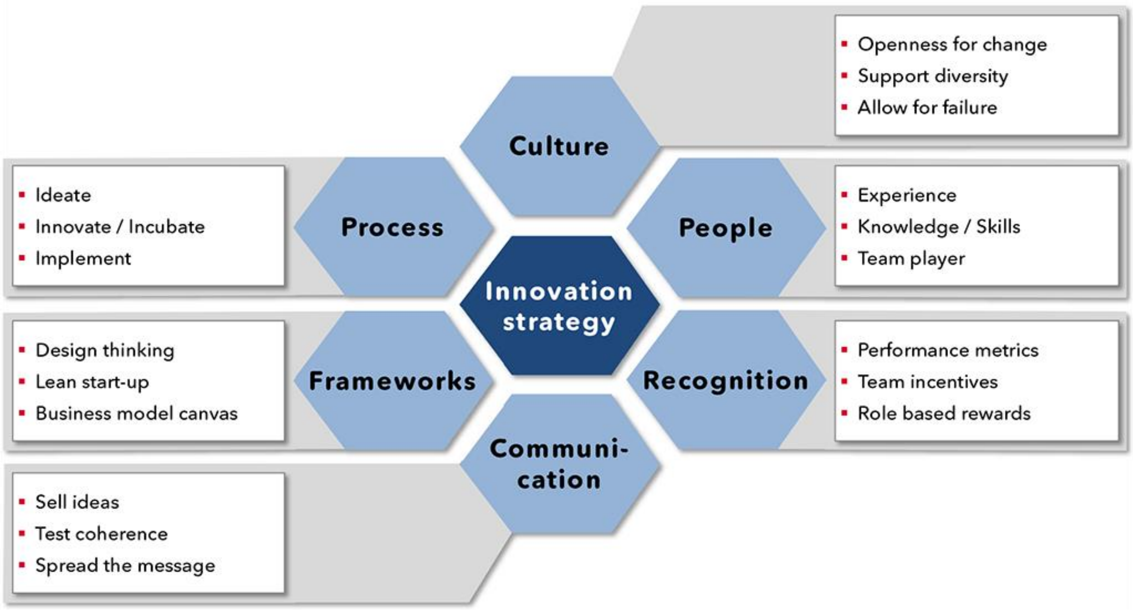


Fig. 5-6: Key innovation capabilities. Source: Innovate-D (2018).

In order to create propose innovative solutions to the identified problems, a few activities can be undertaken:

- Hold ideation sessions and discuss propositions for new solutions to address bottlenecks, taking advantage of the opportunities.
- Translate ideas into technical solutions and assess feasibility.
- Present and validate new service design proposal, incorporating feedback from stakeholders.
- *Milestone: A portfolio of ideas.*

Stevens (2022) recommends being aware of the nature of the design problem, group size and profile of participants before choosing a particular technique, providing some tactic examples in ideation sessions:

a) *analogies*: comparing your situation—or design challenge—to something you are familiar with, enabling you to look at the problem in a new light and consider possible solutions.

b) *bodystorming*: setting up a physical experience resembling the problem you are trying to solve, using people, props, or a digital prototype to generate genuine user empathy.

c) *brainstorming*: verbally bouncing ideas off of each other aiming to find a blended solution.

d) *brainwriting*: writing down ideas and passing them on in the group, leading at the end of a collection of ideas to be discussed.

e) *challenging assumptions*: coming up with a number of assumptions that are inherent to your design challenge and then going through these assumptions and discuss whether they are really true, or if they're simply there because they've never been questioned.

f) *mindmapping*: visual ideation technique that encourages you to draw connections between different sets of ideas or information.

g) *storyboarding*: creating user personas using images and quotes and from there drawing out storylines and outcomes, imagining what the user would feel.

One instance of good practice in innovative policy-design in government is the Brazilian Charter for Smart Cities. Between 2019 and 2021, the Brazilian Ministry of Regional Development (MDR) and the German Cooperation Agency (GIZ) undertook an intense collaborative process. Local governments, other ministries, consultants and civil society organizations were involved in the three 2-day-long workshops where the issues that cities face were discussed and later addressed with specific guidelines. During the sessions, collaborative techniques were used to generate ideas, taking advantage of the diverse background of participants (Przeybilovicz & Pereira Da Silva, 2022).

5.4 The Preparation Phase

5.4.1 Step 5: Data and Capacity Assessment

In the context of digital twinning, the comprehensiveness and quality of data are of paramount importance. Initiatives may commence with data collection; however, it is crucial to first conduct a comprehensive assessment of existing data, either within the organization or from publicly available sources. This data may be spatial or non-spatial and pertain to the built environment, zoning, or regulations.

According to Batini et al. (2009), data assessment methodologies employ two primary types of strategies: data-driven and process-driven. Data-driven strategies focus on improving data quality by directly altering the data values. For instance, outdated data values may be updated by synchronizing a database with a more recent one. On the other hand, process-driven strategies aim to enhance quality by re-engineering the processes responsible for creating or modifying data. A process may be redesigned to incorporate an activity that checks the data format prior to storage. Both data- and process-driven strategies utilize a diverse range of techniques, including algorithms, heuristics, and knowledge-based activities, all designed to bolster data quality. While assessing data quality, the authors propose the assessment of four dimensions:

a) *accuracy*: this refers to the extent to which data are correct, reliable, and certified. Data are considered accurate when the stored values in the database align with real-world values.
b) *completeness*: Completeness is defined as the degree to which a given data collection encompasses data describing the corresponding set of real-world objects.
c) *consistency*: The consistency dimension pertains to the violation of semantic rules defined over a set of data items. In the context of relational theory, integrity constraints represent one type of semantic rule. In the statistical field, data edits are typical semantic rules that enable consistency checks.
d) *time-related dimensions*: data updates over time represent a significant aspect. The main time-related dimensions proposed in the literature include currency, volatility, and timeliness.

Moreover, merely possessing data does not automatically equip a municipality with the capability to utilize it for enhancing its processes. Consequently, it is vital to not only assess the available data but also evaluate the organization's existing capacity in this domain. As defined by the OECD (2006), capacity refers to the proficiency of individuals, organizations, and society as a whole in effectively managing their affairs. In the context of this methodology, capacity denotes a municipality's ability to implement and maintain a digital twin.

Meijer (2019) developed a model for capacity assessment of public innovation capacity in government organization. It is based on the ability to perform five functions: mobilizing, experimenting, institutionalizing, balancing and coordinating. Table 5-1 below presents statements of each of these functions.

Table 5-1: Instrument for measuring public innovation capacity. Source: Meijer (2019).

Function	Statements for self-assessment
Mobilizing	M1. Employees in City X with ideas about data-driven innovation easily find the right persons in the city to jointly realize these ideas.*
	M2. The people in charge of data-driven innovation in City X succeed in engaging companies, researchers and citizens in the development of new ideas.
	M3. City X has a strong structural network of companies, researchers and citizens connected to data-driven innovation.
	M4. The people in charge of data-driven innovation in City X succeed in stimulating the development of new ideas among colleagues in City X.
	M5. City X has a strong network of employees with an interest in data-driven innovation.
	M6. A company, researcher or citizen with good ideas for data-driven innovation easily finds the right persons within City X to develop these ideas further.
Experimenting	I1. City X is successful in setting up experiments.
	I2. City X has societal support (from citizens, NGOs, companies, etc.) for experiments on data-driven innovation.**
	I3. Political institutions in City X – representatives, aldermen – support experiments with data-driven innovation.
	I4. The administrative executives of City X support experiments with data-driven innovation.
	I5. City X makes sufficient funds available for experimenting.
	I6. If necessary, City X engages other governments, companies and societal organizations in experiments around data-driven innovation.

Institutionalizing	R1. City X is successful in scaling up experiments.
	R2. City X adopts data-driven innovation that have proven to be successful on a small scale in the organizational routines.
	R3. City X evaluates experiments with data-driven innovation well.
	R4. City X succeeds in turning experimental collaboration with governments, companies and societal organizations into structural forms of collaboration.
Balancing	B1. City X succeeds in identifying risks, disadvantages and tensions around data-driven innovation.
	B2. City X initiates the public debate about the risks, disadvantages and tensions around data-driven innovation and how to deal with these.
	B3. If there are conflicts, City X is good at mediating conflicts around data-driven innovation.
	B4. In City X, ethical aspects of data-driven innovation are discussed well.
Coordinating	C1. City X makes financial means available for data-driven innovation on a structural basis.
	C2. There is a good exchange of information on data-driven innovation between all actors in City X.
	C3. City X has a culture that stimulates data-driven innovation.
	C4. City X creates the right conditions for data-driven innovation (training, information exchange, instruments, etc.).
	C5. City X has a clear vision on data-driven innovation.
	C6. Political institutions in City X – representatives, aldermen – are prepared to allocate financial means in the budget for data-driven innovation.

In order to verify the maturity of the organization in the implementation of digital twins, the following activities can be undertaken:

- Identify concerned systems/datasets and assess them in terms of content, coverage, ownership, reliability and current users.
- Identify concerned departments/organizations/teams (how many people working, budget availability, expertise, etc).
- Assess the availability of publicly available datasets about the concerned territory.
- Evaluate city maturity level and capacity for digital twin implementation (availability of an open data portal, data viewer, smart city policy, etc).
- Present and validate capacity assessment with stakeholders and internal departments.
- *Milestone: A data assessment report and a capacity analysis report.*

5.4.2 Step 6: Data Collection

An essential element to deliver an urban digital twin is the collection of appropriately accurate and precise high-quality spatial data, including related metadata. In most cases, the data assessment will review the need for data collection. Collecting data from the built environment can be very expensive and there are economies of scale involved. For this reason, often companies are hired to collect data or offer it as a service after the data was collected. However, it is important to mention that in the latter case some restrictions can apply in the use of the data provided. Here under a strategy for successful data collection:

- Identify data needed to successfully perform the chosen use case(s) by involving stakeholders
- Verify financial and technical feasibility of acquiring data, directly collecting it, as well as keeping it updated
- Identify companies in the regional market able to perform the data collection, as well as opportunities for crowdsourcing and collaborative mapping
- Describe in detail the specifications of the data to be collected (coverage, accuracy, data format, customization needs, ownership)
- Follow the collection of the primary data and the data processing flows to ensure quality, if it is the case
- Elaborate a data management plan
- Consolidate the data and make it available to concerned departments and residents in open data portals (when possible/desirable).
- *Milestone: Datasets ready to be integrated to the digital twin.*

Table 5-2: Geographic data collection.

Type of data	Primary data sources	Secondary data sources
Raster	remote sensing images	scanned and digitized maps
	aerial photogrammetry	digital elevation model
Vector	GPS measurements	topographic surveys
	Survey measurements	toponomy/cadaster datasets

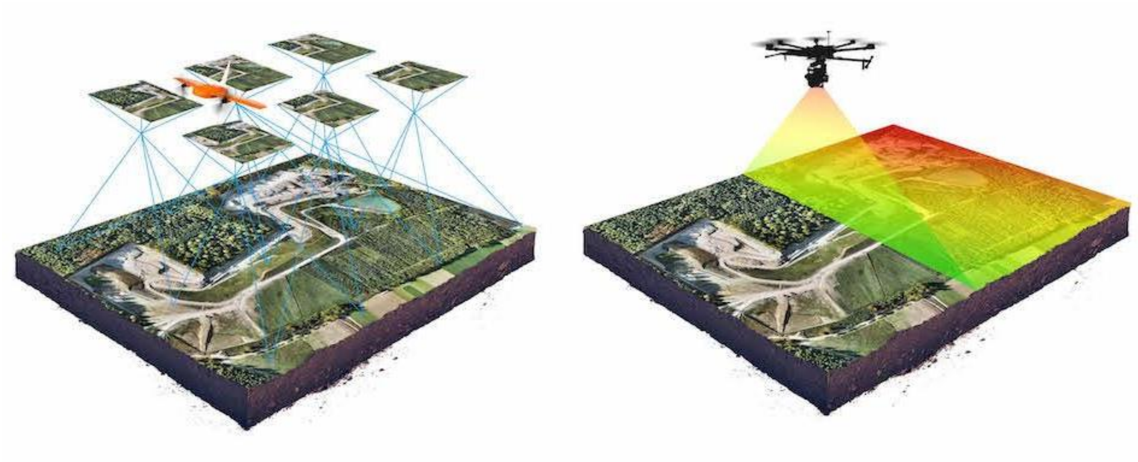


Fig. 5-7: Photogrammetry (left) versus LiDAR (right). Source: (Wingtra, 2023).

By combining aerial imagery and aerial point clouds, the company Cyclomedia created a realistic and periodically updated 3D model of the entire Netherlands. Data collection was assisted by the software Leica CityMapper-2 and the data hosted on Hexagon's HxDR cloud-based visualization platform. Their business model is based on clipping and providing 3D data to multiple parties on-demand. The resolution varies depending on flight restrictions, going from around 3cm to 11cm.

Fig. 5-8: Point-cloud dataset by Cyclomedia. Source: (Cyclomedia, 2023).

5.5 The Implementation Phase

5.5.1 Step 7: Pilot Digital Twin

Even after careful planning and preparation, implementing an urban digital twin can be a challenging task that requires testing solutions. Developing a pilot before going for full implementation is a way to pursue a reasonable efficiency of the invested resources. This step can provide valuable lessons before scaling-up the project. In order to evaluate the collaboration capabilities, it is desirable to choose use cases that encompass more than one theme, focusing on the potential arising from breaking the administrative silos, e.g. mobility, housing, traffic etc. This step consists on the following activities:

- Design architecture of pilot system/platform of a Digital Twin to address the needs of chosen processes (requirements, data storage, federated or unified database, data flows)
- Identify available technologies and suppliers able to provide implementation solutions (viewer, database, data storage, algorithms, etc), finding the right balance between in-house and outsourced development
- Develop a visual prototype with mock-ups to communicate the proposal
- Test features and user interface with actual users
- Identify baseline data to be able to measure the impact of the digital twin
- Develop web-interface and link to datasets
- Update and launch pilot digital twin (a minimum viable product)
- Consolidate lessons learned and update pilot digital twin, making it fully functional and useful to address the pressing issue. Measure the impact of the digital twin in this specific process
- *Milestone: Pilot digital twin operating as a minimum viable project.*

Diakite et al. (2022) developed a prototype digital twin that consolidates existing data using a standardized 3D format, specifically CityGML, and incorporates analytics such as sun exposure and tree coverage for evaluating livability within a 3D city modeling framework. Key urban elements, including buildings, roads, railways, vegetation, and water bodies, were processed and integrated into the model. Furthermore, IoT sensors were incorporated into the model, and all processes utilize open-source tools to enhance accessibility and replicability. The authors also developed python and SQL scripts to pre-process the data and enable the creation of a 3D triangle irregular network (TIN).

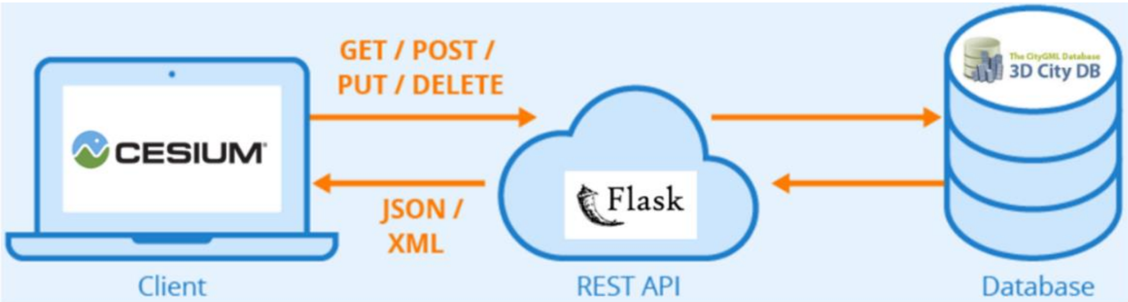


Fig. 5-9: Diagram of API requests between Cesium and 3DCityDB. Source: (Diakite et al., 2022).

Fig. 5-10: Interface of a pilot digital twin. Source: (Diakite et al., 2022).

5.5.2 Step 8: Digital Twin Development

In certain instances, municipalities initiate the development of a digital twin incrementally, while in other cases, a comprehensive digital twin is proposed from the outset to optimize cross-disciplinary collaborations and dismantle data silos. This approach necessitates comprehension and dedication from city officials to steer the process effectively, but it may yield more rapid improvements in quality of life.

Although there is no one-size-fits-all approach to digital twin development, the expectation at this stage is that the organization has already gained knowledge and capacity from previous steps, positioning it to successfully construct an urban digital twin. The main difference in relation to the previous step is that issues such as privacy, performance, security and other related to the up-scaling the platforms need to be handled with a lot of attention. The digital twin development consist on the following activities:

- Extend the scope of the digital twin by incorporating more processes, preferably pressing issues.
- Repeat steps 1-3 regarding the new processes included.
- Design architecture of the comprehensive version of the digital twin (sub-steps: choose technology adopted for the viewer, the database, etc).
- Propose and discuss a management structure to be responsible for decisions regarding the digital twin (e.g. a council assisted by a technical unit within the organization).
- Identify baseline data to be able to measure the impact of the digital twin.
- Develop the digital twin as minimum interoperable module, finding the right balance between in-house and outsourced development.
- Set up a team for maintenance and management of the digital twin.
- Launch gradually new modules of the digital twin, constantly testing and upgrading the platform with permanent room for internal and external feedback.
- Write a strategy to keep the interest of stakeholders met in the operation, in the form of a governance model.
- *Milestone: Operating Digital Twin and Governance Model.*

Rotterdam is an example of city that invested in the development of a comprehensive replica of the city. The core of Rotterdam Urban Data Platform is formed by the city's 3D Digital Twin. This is a description of the current physical reality through data. That starts with the 3D model of the city, in which all fixed physical objects (houses, trees, benches, etc.) in the city are included.

This model is then supplemented with 'live' data on the use of the city. The implementation process was guided by the development of the following minimum interoperability mechanisms - MIM: 1. PPI's /open data models /shared data models, 2. Context information management, 3. Privacy and security management, 4. (Access to) Data storage; 5. Geo-functionality, 6. Data conversion, 7. Open API strategy, 8. Data marketplace, 9. 3D Digital Twin, 10. Governance model (Gemeente Rotterdam, 2023).

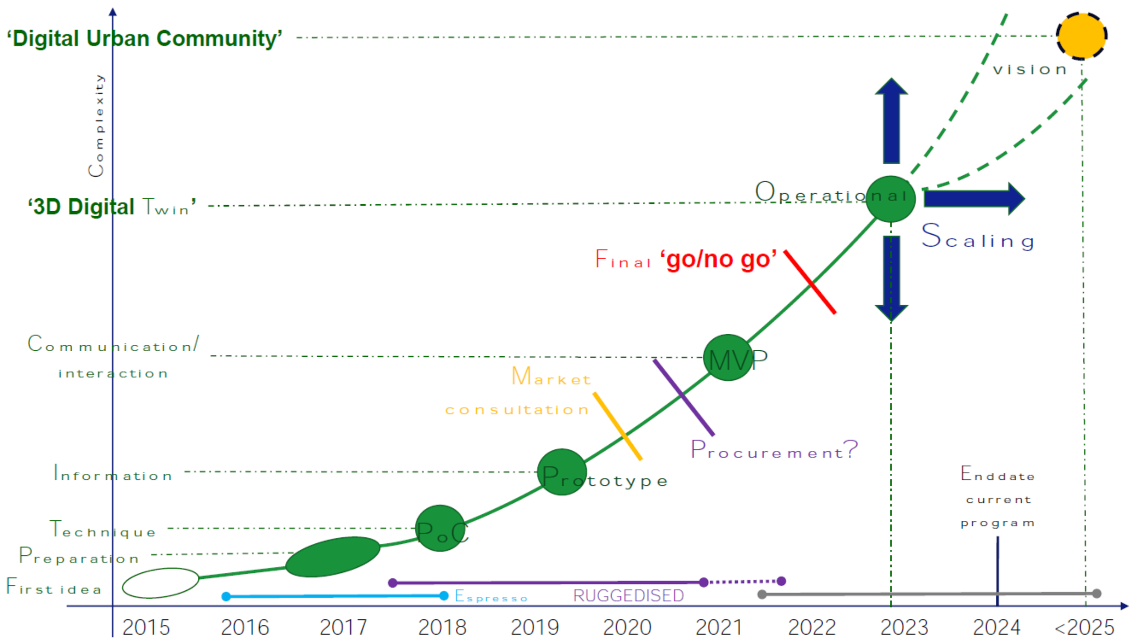


Fig. 5-11: Rotterdam's digital twin development process. Source: (Gemeente Rotterdam, 2023).

5.6 The Operation Phase

5.6.1 Step 9: Digital Twin Operation

Operating an urban digital twin is the next challenge to be faced by municipalities developing this kind of initiative. Even if the operation is undertaken by one or a set of external providers, the operation knowledge needs to be well-integrated into the organization. Most digital twins are seen as projects, with temporary funding but not as part of the city infrastructure. In the near future, as digital twins become mainstream, dedicated teams and even regulations will be more common. In order to successfully operate a digital twin at city-level, the organization can follow the sub-steps below:

- Consolidate digital twin governance model
- Keep track of the digital twin performance and the impact of the digital twin in public services and in the life of city residents
- Hold a permanent channel of communication between stakeholders and the public, fostering a digital community around the digital twin
- Upgrade and incorporate new features demanded by stakeholders
- Constantly consolidate lessons learned and internalize the knowledge in the organization
- *Milestone: Keep operation in the long-term, periodic official coordination meetings and strong governance model.*

There are few examples of digital twins in full operation, but similar initiatives like the control rooms have been operating for years in some cities around the world. According to the Center for Public Impact, Rio de Janeiro Center of Operations (COR) connected more than 50 city agencies, resulting in more cooperative and efficient relationships between them. It connected media outlets to the city government, creating transparency and a streamlined method of publishing information. COR has gained a lot of global media attention, especially during the 2014 World Cup and the 2016 Olympics.

Fig. 5-12: Rio de Janeiro's Center of Operations (COR). Source: (COR, 2023).

5.7 Conclusions

In conclusion, the methodology presented in this chapter offers a comprehensive framework for implementing digital twins within municipal governments, specifically addressing spatial planning and decision-making processes. Recognizing that digital twins represent innovative solutions, their implementation may require transformative organizational changes and an iterative approach to prototyping and testing. The methodology caters to a diverse array of stakeholders, ensuring that each group derives distinct benefits from the content, thereby fostering a more inclusive and informed implementation process.

Moreover, the financing context of these projects significantly influences the implementation steps and methods, highlighting the importance of tailoring the approach based on the available resources and priorities. Comprised of nine steps organized into four major phases, the proposed methodology provides a structured roadmap for planning, preparing, implementing, and operating digital twins in urban contexts. While the steps and phases may overlap in real-world projects, adhering to this methodology will ultimately facilitate the successful integration of digital twins into municipal decision-making processes, promoting data-driven urban planning and enhancing the overall quality of life for city residents.

5.8 References

Batini, C., Cappiello, C., Francalanci, C., & Maurino, A. (2009). Methodologies for data quality assessment and improvement. *ACM Computing Surveys*, *41*(3). https://doi.org/10.1145/1541880.1541883

Bloomberg Philanthropies. (2023). *I-Teams and Innovation Programs*. https://www.bloomberg.org/government-innovation/spurring-innovation-in-cities/i-teams-and-innovation-programs/#:~:text=Bloomberg%20Philanthropies%20funds%20Innovation%20Teams,program%20when%20the%20grants%20ended.

COR. (2023). *Alta tecnologia à serviço do Rio*. https://cor.rio/institucional/

Cyclomedia. (2023). *30+ years of visualizing the real world*. https://www.cyclomedia.com/en/company/history

Diakite, A. A., Ng, L., Barton, J., Rigby, M., Williams, K., Barr, S., & Zlatanova, S. (2022). Liveable City Digital Twin: A Pilot Project for the City of Liverpool (NSW, AUSTRALIA). *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *10*(4/W2-2022). https://doi.org/10.5194/isprs-annals-X-4-W2-2022-45-2022

Gemeente Rotterdam. (2023). *Digitale Stad*. https://www.rotterdam.nl/digitale-stad

Innovate-D. (2018, January). *How to make your company more innovation friendly*. https://www.innovate-d.com/insight-026/

Meijer, A. (2019). Public Innovation Capacity: Developing and Testing a Self-Assessment Survey Instrument. *International Journal of Public Administration*, *42*(8), 617–627. https://doi.org/10.1080/01900692.2018.1498102

Northeastern University. (2020, March 23). *3 Top Project Management Methodologies You Should Know*.

https://www.northeastern.edu/graduate/blog/project-management-methodologies/

OECD. (2006). *The Challenge of Capacity Development: Working Towards Good Practice*. http://gsdrc.org/docs/open/cc110.pdf

Przeybilovicz, E., & Pereira Da Silva, R. (2022). A collaborative approach to formulate a public strategy: The experience of the Brazilian Charter for Smart Cities. *ACM International Conference Proceeding Series*. https://doi.org/10.1145/3560107.3560191

Royal Academy of Engineering. (2020). *Sustainable living places – a systems perspective on planning, housing and infrastructure*. https://raeng.org.uk/media/5h0hlmkj/policy-sustainable-living-v11.pdf

Scrum.org. (2023). *What is scrum?* https://www.scrum.org/learning-series/what-is-scrum

Stevens, E. (2022, December 6). *What Is Ideation in Design Thinking?* https://careerfoundry.com/en/blog/ux-design/what-is-ideation-in-design-thinking/

Thesing, T., Feldmann, C., & Burchardt, M. (2021). Agile versus Waterfall Project Management: Decision model for selecting the appropriate approach to a project. *Procedia Computer Science*, *181*. https://doi.org/10.1016/j.procs.2021.01.227

Visual Paradigm. (2023). *Scrum vs Waterfall vs Agile vs Lean vs Kanban*. https://www.visual-paradigm.com/scrum/scrum-vs-waterfall-vs-agile-vs-lean-vs-kanban/

Wingtra. (2023, January 27). *Photogrammetry vs. LIDAR: what sensor to choose for a given application*. https://wingtra.com/drone-photogrammetry-vs-lidar/

6 . Conclusions and Recommendations

6.1 Final Considerations

This thesis explores the growing interest in digital twins for cities and highlights the diversity of applications and scales at which they can be deployed. The current state of research reveals a focus on use case studies and a research gap in the quantitative data approach and an emphasis on technological aspects over human-centered approaches.

This research addresses these gaps by providing a comprehensive, data-driven analysis of digital twins, offering practical guidance for stakeholders in various contexts. To achieve this aim, the research answers key questions about the effective support of urban planning and management through digital twins and the key factors and challenges in implementing digital twin initiatives at municipal and regional levels.

By addressing these questions, this work provides valuable insights and practical recommendations for city officials, planners, policymakers, and other stakeholders involved in the development of digital twin initiatives, ultimately contributing to the advancement of knowledge in the field of urban digital twins and shaping the future of urban planning and governance.

6.2 Main findings

The literature review highlights the importance of integrating various frameworks and key insights in the development of digital twins for urban environments. By examining the diverse nature of digital twin ecosystems, it emphasizes the need for a shift from top-down approaches to more citizen-centered and decentralized governance strategies, such as federated data models. Emphasizing collaboration, active citizenship, and principles such as purpose, trust, and function can help create more inclusive, adaptable urban environments that harness the full potential of digital twins and related technologies. Successful implementation requires an understanding of the complex interplay between physical representation, data collection, modeling, simulations, and decision-making, as well as a focus on fostering quadruple helix cooperation, ensuring privacy, and promoting community-oriented thinking.

The comprehensive global assessment of digital twins indicates that the development of digital twins is taking place independently in different organizations, with limited cross-multidisciplinary use cases. As the industry progresses along the maturity spectrum, there is potential for growth and innovation, especially regarding autonomous operations. The regional breakdown indicates that the focus of digital twins is highly influenced by the unique socioeconomic, political, and cultural contexts of each region, which can inform the development and implementation of national and international digital twin policies. For example, the diversity in use cases and predominant exploratory level of digital twins in Europe reflects available funding for research but also reveals challenges in scaling up and implementing integral digital twin solutions.

The detailed analysis of the vibrant Dutch digital twin ecosystem reveals an inspiring set of municipalities working on digital twin projects, with goals such as integrating legal, administrative, and physical realities, improving communication with residents and project initiators, enhancing data-based scenario creation, and preparing for the new spatial and environmental planning ordinance. There are technology-pioneering initiatives, a growing market for new service providers, and a consensus on avoiding vendor lock-in and adhering to standards. However, shortcomings exist in the integration of citizens into digital twin design and implementation, and the extent to which these projects have improved citizens' quality of life remains unclear.

6.3 Contributions

The comprehensive global assessment of digital twins offered unique and unprecedented insights into the development of this technological breakthrough, though limitations such as the underrepresentation of Eastern languages and the subjective analysis of maturity levels remain. It sheds light to the majority of digital twin initiatives that are less documented and not mentioned on academic papers.

By examining the state-of-the-art of spatial digital twins worldwide, this assessment provides valuable insights into their potential to revolutionize urban management, planning, and sustainability. By evaluating and learning from global experiences, it is possible to harness the power of digital twins to create more resilient, efficient, and sustainable cities for the future.

The knowledge gained during the research enabled the author to propose a structured strategic methodology for digital twin implementation at the city-level. The proposed approach acknowledges often undermined practical factors typical from governmental organizations and the need for transformative organizational changes and iterative prototyping in response to the innovative nature of digital twins. By catering to diverse stakeholders, the methodology fosters an inclusive and informed implementation process. It consists on a structured roadmap for digital twin integration in urban contexts, ultimately promoting data-driven urban planning and enhancing the overall quality of life for city residents.

6.4 Further research

As a suggestion for further research, other aspects like the supported data formats, budget and time for implementation among digital twin initiatives from all around the world would provide an even deeper insight into this industry. The explorations of the reasons behind the openness of the digital twin source code, data and access to the interface would help city officials make more grounded decisions on how and when to open up their initiatives.

As digital twin implementation at city level evolves, further research on the actual followed steps and choices would help providing a more accurate guide for implementation, assisting organizations on addressing even more complex issues at a large scale by using virtual replicas of processes and physical elements of the real world.

As every tool, digital twins do not have an end on itself, measuring the impact of this technology to people's lives is very important. As a public infrastructure, its added value is not always clear and easy to measure, but the development of structured impact measurement methodologies is worth the effort. It is also a matter of time before digital twins all around the world reach a higher maturity level and explore the capabilities and economies of scale of autonomous operations. It raises many privacy and ethical issues that should be addressed in further research.

Appendix:

DIGITAL TWIN ASSESSMENT TEMPLATE

This assessment template aims to gather information about ongoing digital twin initiatives regarding the built environment from across the world. The goal is to draw a picture of adopted technologies, design process and management models for Digital Twins within companies and municipalities.

A. RESPONDENTS

A1. **Name**	
A2. **Contact information**	
A3. **Position in the Organization**	
A4. **Role in the DT Project**	1. ( ) Project Coordination 2. ( ) Project Assistant 3. ( ) IT Specialist 4. ( ) Urban Development/Planning Specialist 5. ( ) Other:__
A5. **Date of intake**	

(If more than one respondent in the same DT, add here)

B. CITY/REGION DATA

B1. **Country**	
B2. **Population**	
B3. **GDP per capita** (US$)	
B4. **Area of the Municipality** (km^2)	

B5. **Important websites (if existing)**	1. Main municipal portal: 2. Smart City department/initiative website: 3. DT website: 4. Access to the DT: 5. Smart City Strategy: 6. Open data portal: 7. Guidelines for DT at the national/regional level:
B6. **What is the official DT definition for the project?**	
B7. **Is there a Smart City Strategy?**	*E.g. Approved/Ruling; Under Development; Planned; Not existent and not planned*
B8. **Guidelines for DT at the national/ regional level?**	*E.g. Approved/Ruling; Under Development; Planned; Not existent and not planned*
B9. **Is there an open data portal held by the municipality? Does it include 3D data?**	*E.g. Yes and includes 3D; Yes, but does not include 3D data; Under Development; Planned; Not existent and not planned.*

C. ADMINISTRATIVE CONDITIONS

C1. **Is there any use case for the DT Platform already?**	*E.g. Urban planning/ urban design; Utility/infrastructure management; Traffic management; Asset management; Community engagement; Environmental monitoring; Public safety; Permitting or other internal municipal processes.*
C2. **Which phase best describes the status of the DT project at this moment?**	*E.g. Proof of Concept (internal concept of what can be done); Prototype (working and interactive product of how it is done, mainly internal); Operational Product (already serving the need it was designed to meet)*

C3. **Is there an administrative unit responsible for the DT? How many professionals work full time (or most of their time) in the DT project?**	*(Include the name of the unit. Is it a core team within a unit? Or include professionals from different units?)*
C4. **Does the DT have a thematic approach?**	*E.g. Multi-purpose approach OR logistics; transportation; disaster management.*
C5. **Was there any engagement of non-technical professionals (lawyers, social sciences, etc)**	*E.g. At early stage; After the first prototype; No, but planned; Not planned)*
C6. **Important milestones** (year)	• Kick-off of the DT project: • Prototype was launched internally: • DT was launched within the organization: • DT was launched to a broader public:
C6. **Financial resources invested in DT** (local currency)	*(It can be an estimate if value is not known)*
C7. **Is there continuous funding for DT initiative?**	*E.g: Yes, continuous funding secured; Funding based on an external grant for the next 1-3 years; No funding secured for further development.*
C8. **What is the DT Maturity Level?** (choose the one that most represents the DT project at this moment)	1. ( ) Spatial data repository with geoservices 2. ( ) Visualization platform 3. ( ) 3D visualization platform 4. ( ) Data analysis platform (provides insights analyzing data from different sources) 5. ( ) Platform enriched with real time data from sensors/other sources 6. ( ) Actuation-enabled (control devices in the physical world) 7. ( ) Any autonomous operation or artificial intelligence-enabled

C9. **How is the DT managed?**	*E.g. A federated model coordinated by one or many entities; A single entity; No defined management model yet.*
C10. **What are the DT territorial limits?**	*E.g. A whole municipality/region; A district within a municipality; Any other.*
C11. **Is there any University/ Research Institution involved in the project?**	*(If yes, which ones and how they are involved)*

D. ENTITIES AND THEIR ROLE IN THE DT ECOSYSTEM

According to Griffith & Truelove (2021), DT ecosystems can be understood by the interaction of some types of stakeholders.

D1. **DT platform/ application operator:** responsible for developing, operating and maintaining a digital twin platform or application	• *(E.g.: Bentley, ESRI, IBM, the municipality)*
D2. **DT data custodians/ owners:** collects, generates, maintains data for the purpose of carrying out their functions.	• *(E.g.: Utility company, a city department)*
D3. **DT data service providers:** provides digital twin data services to data custodians or digital twin platform operators.	• *(E.g.: cadaster institution, GoogleMaps)*

D4. **DT data users:** end-user of the digital twin platform, which are able to draw insights and decision support about issues of interest.	• *(E.g.: mayor's office, citizens, utility companies, planning department)*

E. DT QUADRUPLE HELIX ENGAGEMENT

	E1. **Engagement in DT Planning/ Design Phase**	E2. **Access to DT**	E3. **Engagement in DT Operation/ Management**
Government	( )	( )	( )
Companies	( )	( )	( )
Citizens	( )	( )	( )
University/ Research Institutions	( )	( )	( )
Any comments on the stakeholder engagement process?			

F. TECHNOLOGIES ADOPTED (technical)

F1. **What is the technology adopted for the viewer?**	*(E.g.internally developed solution based on Cesium, Mapbox; ArcGIS Urban, ARCGIS Javascript API, Bentley OpenCities Planner; other)*
F2. **Is it a commercial solution? What is the licensing model?**	*(E.g. annual or monthly subscription; full solution was purchased)*

F3. **What is the Level of Detail - LOD for most buildings?** (If the viewer includes 3D buildings)	( ) LOD 0 ( ) LOD 1 ( ) LOD 2 ( ) LOD 3 ( ) LOD 4 
F4. **How is the DT data stored?**	*(E.g. cloud-based or local storage? Amazon AWS, ESRI, Azure, etc)*
F5. **What is the type of database and solution adopted?**	*(E.g. Relational, NoSQL, PostGRES, MongoDB, etc)*
F6. **Is there any platform of middleware for IoT?**	*(If yes, which one?)*
F7. **Which data formats are inputs of the DT?**	• ( ) CityGML • ( ) CityJson • ( ) GIS shapefiles (.shp, sdf, .gdb, .geojson…) • ( ) CAD files (.dwg, .fbx...) • ( ) 3D files (.skp, .3dm..) • ( ) Cesium 3D tiles • ( ) BIM files (.ifc, .rvt…) • ( ) Tables (.xlsx, .csv) • ( ) Other:___
F8. **Which data formats are outputs of the DT?**	• ( ) CityGML • ( ) CityJson • ( ) GIS shapefiles (.shp, sdf, .gdb, .geojson…) • ( ) CAD files (.dwg, .fbx...) • ( ) 3D files (.skp, .3dm..) • ( ) Cesium 3D tiles • ( ) BIM files (.ifc, .rvt…) • ( ) Tables (.xlsx, .csv) • ( ) Other:___
F9. **Which are the DT Features** (choose all that apply)	• ( ) Dashboards • ( ) Displays real time data • ( ) Interactivity (with widgets) • ( ) Export data • ( ) Export 3D data • ( ) Enable data downloads to the public • ( ) Apply queries in one dataset • ( ) Apply combined queries in multiple datasets at a time

F10. **Is there a DT API for third parties so they can build upon the platform?**	1. ( ) Yes 2. ( ) Planned 3. ( ) No
F11. **How did the DT address interoperability in its design**	*(E.g. Use open data formats, follow a national/international standard)*
F12. **How did the DT address privacy in its design**	

G. PROJECT DEVELOPMENT PROCESS

G1. **Was there a Digital Twin vision and principles guiding the process?**	
G2. **Is there a framework or architecture of what would be the DT when fully implemented?**	*(E.g. Project planned as a whole or in specific modules)*
G3. **Was there any procurement necessary?**	*(E.g. Traditional method; Innovative method; no procurement yet; no procurement planned; Whole platform was procured, only modules were procured)*

H. FINAL REMARKS

H1. **Did the DT change any processes at the organization so far?**	
H2. **Is there any measurement of positive impacts/ added value of the DT?**	

H3. **Which were the main challenges faced by the DT project?**	
H3. **What are the next steps for the DT initiative?**