MASTER

Developing a framework for municipalities on how to develop a Digital Twin for managing environmental entities in the public space and providing real-time insights into sensor data
A pilot for the department 'public space' of the municipality of Weert

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DIGITAL TWINS

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STATEMENT
The thesis has been carried out in accordance with the rules of the TU/e Code of Scientific Integrity. In addition, this master thesis is for public viewing.

PREFACE

In front of you lies the master thesis "Developing a Digital Twin for managing environmental entities in the public space and providing real-time insights into sensor data: A pilot for the department 'public area' of the municipality of Weert." The aim of the research is to create a blueprint for municipalities to develop a Digital Twin capable of managing environmental entities in the public space. It was written to fulfill the graduation requirements of the Urban Systems & Real Estate program at the Technical University of Eindhoven. I was involved in the research and writing of this thesis from November 2022 to July 2023.

This thesis is a result of the knowledge I gained during my HBO Bachelor Civil Engineering and the following Pre-Master and Master Urban Systems & Real Estate. I noticed that during my studies I always tried to approach problems in a practical way. Therefore, this thesis is more practical than theoretical.

I would like to thank my two supervisors, Aloys Borgers and Gamze Dane, as well as the external supervisor Marco van Dijk for the feedback during the initial setup of the thesis and during its execution. I would also like to thank Patrik Trines, Program Director of the municipality of Weert, for giving me the opportunity to carry out this research in collaboration with the department *Public Space* of the municipality of Weert. Without their cooperation I would never have been able to complete this research.

Nino Kamphuis

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SUMMARY

The efficient management and planning of public spaces is a major challenge for municipalities. This research proposes the use of a Digital Twin, combined with Geographic Information Systems (GIS), as a solution. A Digital Twin is a virtual replica of a physical object or system that allows for the analysis and optimization of its performance. By developing a Digital Twin specifically tailored for municipalities to manage environmental entities in public spaces, this research aims to overcome existing data management issues and provide a unified platform for collaboration.

The literature review delves into the concept of Digital Twins, highlighting their origins in the aerospace industry and their applications in various fields, including smart cities. Digital Twins can be used at different levels of sophistication, ranging from virtual prototypes during the design process to autonomous analysis for real-time planning and decision making. In urban spaces, Digital Twins offer numerous benefits, including improved coordination, smart technology integration, and real-time monitoring of environmental conditions, pollution levels, and infrastructure wear and tear.

The research includes insights from interviews with managers responsible for managing environmental entities in the municipality of Weert, the Netherlands. The interviews reveal various requirements and expectations for Digital Twins in cities, such as predicting maintenance needs, simulating growth, and integrating citizen reports. By addressing these needs, a Digital Twin can optimize resource allocation, improve maintenance planning, and create sustainable urban environments.

The development process of the Digital Twin framework includes six main stages: data collection, data processing, model creation, integration, updating, and visualization. Feature data collected from public sources and internal databases form the foundation of the Digital Twin, while real-time sensor data from various sources, such as parking occupancy and noise levels, enhance its functionality. The system architecture incorporates ArcGIS software to enable data management, visualization, analytics, and AI integration.

A pilot implementation of the Digital Twin in the Molenakker neighborhood of Weert demonstrates the potential of the framework. The pilot involves collecting and processing data, creating a 3D representation of the area, integrating real-time sensor data, and providing a comprehensive visualization interface. Feedback from city managers during a post-evaluation presentation helped refine the Digital Twin's features and address implementation challenges.

Based on the study's conclusions, recommendations for the city of Weert include establishing a well-structured information management process that incorporates Digital Twins, BIM and GIS technologies. The municipality should invest in the implementation of Digital Twins on a larger scale, using the lessons learned from the pilot project. Other suggestions include improving data management practices, building a robust system architecture, fostering stakeholder collaboration, and promoting training and knowledge sharing for successful implementation and use of Digital Twins in public space management.

However, there are limitations to this research. Budget, knowledge and time constraints hindered the full implementation of expressed desires and requirements, potentially limiting the comprehensiveness of the findings. Challenges in accessing sensor data due to external stakeholder paywalls limited critical data availability, and limited research was conducted on parking management, due to study scope and data limitations. Future studies should address these limitations by considering stakeholder expectations, exploring alternative data access methods, and expanding the scope of the research for a more comprehensive understanding of Digital Twins in public space management. Therefore, caution should be exercised when interpreting and applying the research findings to real-world scenarios. Further research efforts should aim to overcome these challenges and improve the practicality and applicability of Digital Twins for effective public space management. By addressing these limitations, municipalities can unlock the potential of Digital Twins to revolutionize urban planning, construction, and infrastructure management, resulting in improved decision-making, optimized resource utilization, and the development of smarter and more sustainable cities.

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1 INTRODUCTION

One of the challenges municipalities face is the management and planning of the public space. Public spaces includes civil engineering structures, roads, pedestrian areas, sidewalks, green spaces, surface water, as well as the underground infrastructure that includes sewers and cables for electricity, data, and other services. All of these environmental entities need to be maintained and managed by municipalities and their stakeholders, which can result in large collections of data that need to be accessed and shared with different engineers and managers across multiple domains. A well-structured information management process is therefore critical to accessing the required data at the required time, in the right format, and across multiple domains (Moretti et al., 2022). Nevertheless, the Architecture, Engineering, Construction, and Operations (AECO) sector remains passive, hindered by outdated procedures that impede collaboration and resource utilization across multiple domains (Pärn et al., 2017). An example of these outdated practices is the use of separate files that represent part of an entity in 2D/3D CAD drawings, PDFs, or simply text documents that are shared via email or shared (online) folders. This can result in incomplete data, unwanted copies, or lost data.

In recent years, new technologies have emerged to manage the built environment, including Building Information Modeling (BIM). BIM is essentially a shared 3D database that provides the ability to manage an environmental entity throughout its life cycle, including the design, construction, operation, management, and maintenance phases (Doumbouya et al., 2017). BIM combined with GIS (Geographical Information Systems) is able to represent an environmental entity in 3D at the correct geographical location within a city (Wang et al., 2019).

One of the most recent technological inventions for the management of the built environment is Digital Twins. A Digital Twin is a virtual replica of a physical object or system that is used to analyze and optimize its performance. Digital twins are created by collecting real-time data about the physical asset and using it to build a detailed, virtual model that is constantly updated as new data is collected from the physical asset. This virtual model can be used in a variety of industries to improve efficiency, reduce costs, and enhance the performance of physical assets and systems (Jones et al., 2020). The concept of the Digital Twin originated in a presentation at the University of Michigan in 2002, where it was presented as the formation of a production lifecycle management (PLM) center. It was simply referred to as a conceptual ideal for PLM, but it included all the elements of the Digital Twin as we know it today, including a real space, a virtual space, a link between these spaces, and their subspaces for data and information flow (Grieves & Vickers, 2016). This concept was later referred to as the Information Mirroring Model (Githens, 2007). However, it was later referred to as the Digital Twin due to the way the co-authors described this model. Grieves and Vickers (2016, p. 4) define the Digital Twin as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro-atomic level to the macro-geometric level". At its best, a Digital Twin can provide any information that a physically manufactured product could provide if inspected. Digital Twins are classified into two types: Digital Twin Prototype (DTP) and Digital Twin Instance (DTI). A Digital Twin Environment (DTE) is used to run Digital Twins. The DTP describes the prototypical physical artifacts, while the DTI describes a specific corresponding physical product to which an individual Digital Twin remains linked throughout the lifetime of that physical product. The DTE is a multi-domain, integrated physics application space that can be used to operate on Digital Twins for a number of tasks.

The Digital Twin developed in this research is more like a DTE as it is responsible for managing the physical environment, therefore it can be compared to the Digital Twin Physical Environment (Digitale Tweeling Fysieke Leefomgeving) represented by Geonovum (2021), which is defined as an intelligent, dynamic and digital representation of the physical environment with user-friendly visualization of the surface and subsurface. This model allows the different disciplines within the municipality to manage and share their data. The Digital Twin represents the current and desired physical environment through data, models, and visualization. In addition, the model can predict, calculate and simulate the consequences of interventions when sufficient data and models are added, enabling faster decision making and supported solutions. The Digital Twin also helps managers efficiently manage and maintain physical assets through effective monitoring.

1.1 PROBLEM STATEMENT

The adoption of a Digital Twin to manage the environmental entities of the public space is critical for several overarching reasons. While Digital Twins have shown promising results in improving energy consumption, traffic flow, and supporting development plans in cities such as Singapore and Xiong'an, there is a lack of comprehensive research on how to technically develop a Digital Twin specifically for municipalities (World Economic Forum & China Academy of Information and Communication Technology, 2022). The existing examples highlight the possibilities of Digital Twins, but do not provide a clear methodology for their development.

In the municipality of Weert, data representing environmental entities are currently managed by different teams, including Water & Sewerage (Water & Riolering), Green & Waste (Groen & Afval) and Road infrastructure (Weginfra). Each of these teams use their own tools and store data in different locations. This fragmented approach hinders efficient data sharing, accessibility and collaboration between teams. While the adoption of Geographic Information Systems (GIS) has standardized data storage to some extent, teams still face challenges in effectively integrating their data sets.

The use of ESRI shape files, a common GIS file format that contains the location, shape and attributes of geographic features (ESRI, n.d.), has improved data management within the municipality. However, the current system relies on a 2D viewer called Kaartviewer, which has limitations. It lacks support for 3D visualization, and each team must upload copies of their work to the viewer separately, leading to potential data discrepancies, errors, and omissions (GeoNovation KaartViewer©, n.d.). Manual uploading increases the risk of incomplete or outdated data, which compromises the overall accuracy of the system.

To address these challenges, implementing a Digital Twin can provide significant benefits. A Digital Twin provides a unified platform where data from different teams can be seamlessly integrated, eliminating the need for redundant copies and reducing the risk of data inconsistencies. By harnessing the power of real-time sensor data, a Digital Twin enables managers to gain valuable insights into the public space and its environmental entities. In addition, an easy-to-use dashboard within the Digital Twin allows managers to effectively monitor and analyze data. They can make informed decisions, identify patterns, and proactively address issues related to energy consumption, traffic flow, waste management, water systems, and other environmental factors. The Digital Twin acts as a virtual replica of the physical environment, allowing managers to simulate and test different scenarios before implementing them in the real world.

Developing a methodology for creating such a Digital Twin in Weert is crucial. It involves identifying the most suitable tools, determining the necessary data sources and establishing data integration processes. By defining a standardized approach to Digital Twin development, Weert can streamline data management, improve collaboration and unlock the full potential of its environmental units. Ultimately, this will lead to more efficient use of resources, improved sustainability, and a better quality of life for the residents of Weert.

1.2 RELEVANCE

Research on the development of Digital Twins for municipalities to manage environmental entities in the public space has significant relevance for both scientific advancement and societal implications. Digital Twins offer a transformative approach to urban planning and infrastructure management, enabling municipalities to optimize decision-making, resource utilization, and maintenance planning. By filling a critical knowledge gap, this research contributes to effective public space management and sustainable urban design by promoting informed and data-driven decision-making processes.

The implementation of the "Omgevingswet", an environmental law in the Netherlands, serves as a pertinent backdrop to the importance of this research. Although it is considered a seemingly "simple" law, its implementation has resulted in a "complex" change, requiring extensive preparation and a significant investment of time. The Omgevingswet initiates a comprehensive transition to new processes and collaborative structures, which significantly affects all levels of governance. This transition reduces the autonomy of physical domain departments in municipalities and provinces, requiring continuous consultation to achieve local adaptation. As a result, public servants in this domain must acquire essential skills in collaboration, communication, problem solving, and adaptability to effectively navigate this evolving landscape.

In the midst of these changes, research on Digital Twins has the potential to address the challenges posed by the Omgevingswet. By providing municipalities with advanced technological tools and data-driven approaches, Digital Twins offer the means to optimize public space management and urban design. In addition, they foster collaboration and facilitate continuous consultation, which is in line with the requirements of the new legislation. The research findings and insights can serve as a valuable foundation for municipalities to harness the potential of Digital Twins, enabling them to efficiently adapt to the complexities of the changing environmental and governance landscape. Ultimately, through the use of Digital Twins, municipalities can work towards creating more sustainable and resilient urban environments and meet the demands of the future with agility and foresight.

1.3 RESEARCH QUESTIONS

In order to gather the necessary knowledge for the development of a Digital Twin for municipalities to manage environmental facilities in the public space, a main question and corresponding sub-questions are formulated. These questions represent the sequential steps that will be taken during the research process. By explicitly stating the sub-questions up front, a clear understanding of the scope and complexity of the research problem is demonstrated and a logical progression in addressing the research objectives is established. The sub-questions are answered through a combination of theoretical literature review, practical research involving interviews, and software exploration. This approach ensures a thorough exploration and understanding of the topic. The main question and associated sub-questions are defined as follows:

What methodology is required for a municipality to develop a Digital Twin that allows managers to manage the environmental entities in the public space and provide insights from real-time sensors?

SUB-QUESTIONS

- What is a Digital Twin?
- What are Digital Twins used for in urban space?
- What methods are currently used to manage the environmental entities of the public space?
- What are the expectations and desires of municipalities regarding Digital Twins?
- How can a Digital Twin be used to manage the environmental entities of the public space?
- What are the benefits of using Digital Twins compared to current management methods?
- What data needs to be collected for the development of a Digital Twin to manage the environmental entities of the public space?
- What tools are required for the development of a Digital Twin to manage the environmental entities of the public space?
- What sensor data can be included in a Digital Twin?
- How can a Digital Twin be presented in a user-friendly dashboard?
- How can a Digital Twin be implemented in a small Dutch city?

1.4 READING GUIDE

The thesis is divided into several chapters, each covering a specific aspect of Digital Twins in the context of municipal management.

- Chapter 1 lays the foundation by highlighting the challenges faced by municipalities, the need for well-structured information management processes, and the limitations of traditional methods.
- Chapter 2 provides a comprehensive literature review and examines case studies of Digital Twins. It explores their applications in various fields and focuses on their use in urban spaces, including construction, facilities management, and urban planning. Real-world examples are presented to illustrate the practical use of Digital Twins in these domains.
- Chapter 3 focuses on the processes and data collection methods of the municipality of Weert in the Netherlands. Through interviews, insights are gained into the tasks, data management practices, and perspectives of individuals responsible for managing environmental entities in the public space. This information serves as a basis for understanding the requirements and desires for the implementation of a Digital Twin in the municipality.
- Chapter 4 outlines the six main stages involved in developing a Digital Twin for managing environmental entities in the public: data collection, data processing, model creation, integration, updating, and visualization. Each stage is described in detail, emphasizing the importance of accurate and comprehensive data collection and processing.
- Chapter 5 focuses on the system architecture required to implement a Digital Twin in municipalities. It discusses the software suite used for this research, ArcGIS, and explores the capabilities of ArcGIS Pro and ArcGIS Online for data management, visualization, analysis, and collaboration.
- Chapter 6 presents a pilot study conducted in the Molenakker neighborhood within the municipality of Weert. This pilot area serves as a testing ground for the framework described in Chapter 5 and demonstrates the data collection, processing, modeling, sensor data integration, and visualization capabilities of the Digital Twin.
- Chapter 7 concludes this thesis by summarizing the main steps and findings, answering the research questions, a critical review of the results and recommendations for further research and development.

2 LITERATURE REVIEW & CASE STUDIES

This section describes the literature review on Digital Twins. It begins with a review of the literature explaining Digital Twins in general, followed by a review of the literature based on sensor integration of Digital Twins for different purposes. This is followed by a more detailed look at Digital Twins in the urban space, followed by a review of examples from cities and ports around the world. The concluding section highlights the relevant and missing information in the literature.

2.1 DIGITAL TWINS

Boje et al. (2020) state that the use of Digital Twins, which are digital representations of physical assets that allow for their monitoring and control throughout their lifecycle, has gained popularity with advances in technology. While many applications of Digital Twins have been explored in the BIM field, the Digital Twin paradigm requires a higher level of detail and accuracy, ranging from small, manufactured assets, buildings, and neighborhoods to potentially nationwide Digital Twins (Bolton et al., 2018).

The concept of the Digital Twin was first introduced in the early 2000s by Dr. Michael Grieves, a researcher at the University of Michigan. He coined the term "Digital Twin" to describe a virtual representation of a physical asset or system that can be used for a variety of purposes, including monitoring, analysis, and simulation (Grieves & Vickers, 2016). The Digital Twin concept, on the other hand, was first published in the aerospace field, where it was defined by Tuegel et al. (2011) as "a reengineering of structural life prediction and management". Since then, it has been applied in other fields such as product manufacturing and smart cities (Mohammadi & Taylor, 2017). Studies have referred to Digital Twins as "cyber-physical integrations," and the term "system of systems" is also sometimes used to describe their scalability and sustainability (Tomko & Winter, 2018). The main components of a Digital Twin are the physical components, the virtual models, and the data that connects them (Grieves & Vickers, 2016). These components are often referred to as the Digital Twin paradigm (Semeraro et al., 2021). This concept describes the process of data flow between physical and virtual components, allowing the virtual asset to use embedded engineering and AI to discover information to manage the physical asset. Figure 1 shows a visualization of the Digital Twin paradigm, including the various data flows between the virtual and physical assets.

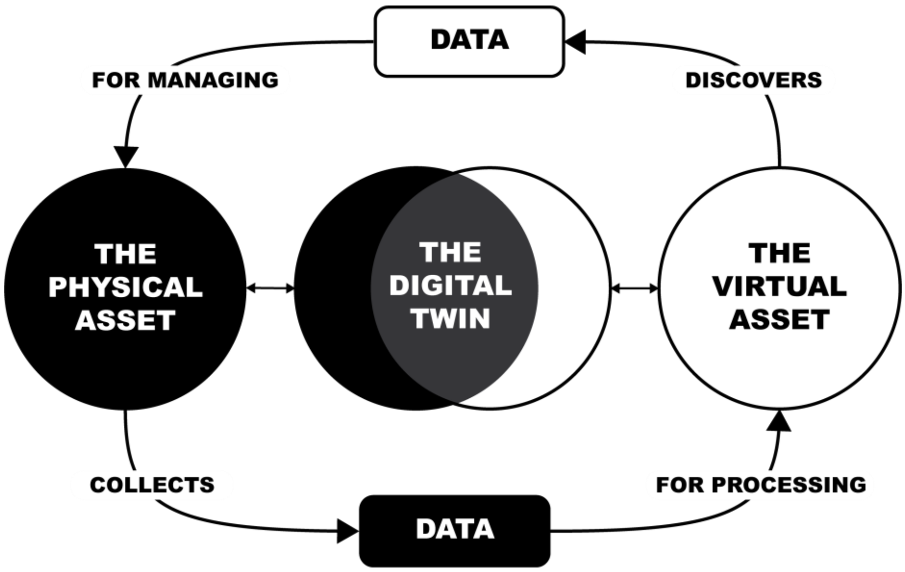

Figure 1 The Digital Twin Paradigm

The functionality and characteristics of a Digital Twin are generally expected to be consistent across industries and applications. Although there has been a resurgence of interest in the concept of a Digital Twin, research in this area is still limited. However, many older concepts and applications are being repurposed and rebranded as components of Digital Twins due to the growing need for interoperability, automation, and intelligent systems (Boje et al., 2020).

2.2 LEVERAGING DIGITAL TWINS

Madni et al. (2019) define Digital Twins in four levels to describe their level of sophistication, using the example of model-based systems engineering (MBSE). It is suggested that a Digital Twin should be considered from a technological perspective in the context of its application domain. For example, an engineering Digital Twin should use different models, tools, and technologies than a manufacturing Digital Twin. However, the overall architecture and functionality of a Digital Twin is expected to be consistent across industries.

The first level described by Madni et al. (2019), Level 1, is the initial virtual prototype created during upfront engineering. It is a generic, virtual model of the intended system that is created before the physical prototype is built. The primary purpose of this virtual prototype, also known as the pre-Digital Twin, is to identify and mitigate technical risks early in the design process. Unlike other model-driven approaches, a virtual prototype is typically not used to develop the final system. Instead, it is often a "throwaway" prototype used to validate key design decisions and reduce technical risk. However, it can also be a "reusable" prototype that can be used to develop the final system. A simple, low-fidelity model of a car created in Modelica using the Planar Mechanics library is an example of a Level 1 virtual prototype. This model includes basic components such as wheels, a differential, and sensors to measure position, velocity, and acceleration. It can be used to test and evaluate trajectory control algorithms in autonomous vehicles.

Level 2 is a Digital Twin that incorporates performance, health, and maintenance data from the physical twin. To support high-level decision making at various stages of the design process, the virtual representation, an instantiation of the generic system model, receives batch updates from the physical system. This data includes information about the physical system's health (e.g., battery level) and mission performance (e.g., flight hours), which is used to update the virtual model and maintain the physical system. Since the digital and physical twins can interact with each other, the physical twin can also use the knowledge gained from one or more Digital Twins to improve its performance during operation. Level 2 Digital Twins are frequently used to investigate the behavior of the physical twin in a variety of scenarios. Any flaws discovered can be fixed by modifying the physical twin, and the changes will be reflected in the Digital Twin. An example of a Level 2 Digital Twin is a model of a passenger car with a power split hybrid powertrain. This model includes components such as wheels, a differential, and a power split device, as well as sensors and other virtual components. The model is based on data from the physical twin, allowing it to accurately represent the behavior of the physical car.

Level 3 is the Adaptive Digital Twin. It includes an adaptive user interface that can learn and adapt to the preferences and priorities of the user or operator. This is achieved using a neural network based supervised machine learning algorithm. The models within this Digital Twin are updated in real time based on data from the physical twin. This allows the Digital Twin to support real-time planning and decision making during operations, maintenance and support. The adaptive user interface makes the Digital Twin sensitive to the context in which it is used, allowing it to provide personalized and relevant information to the user.

Level 4 is the Intelligent Digital Twin. It includes all the capabilities of a Level 3 Digital Twin, such as supervised machine learning, but also has unsupervised machine learning capabilities. This allows the Digital Twin to recognize objects and patterns in its operational environment and to learn from its experience in uncertain and partially observable environments. This level of Digital Twin has a high degree of autonomy, allowing it to analyze more detailed performance, maintenance, and health data from the physical twin. In addition to its machine learning capabilities, the Level 4 Digital Twin can also support real-time planning and decision-making in various contexts.

Overall, the four levels of Digital Twins described by Madni et al. (2019) provide a framework for understanding the increasing sophistication and capabilities of Digital Twins, highlighting their potential in various industries and applications.

2.3 SENSOR INTEGRATION INTO DIGITAL TWINS

The integration of sensors into Digital Twins has emerged as a transformative approach to improving planning, management, and sustainability in a variety of domains, including cities, industries, and infrastructure. By integrating sensors into digital representations, organizations can collect real-time data, monitor environments, and make informed decisions based on accurate and up-to-date data.

Sensors play a critical role as the eyes and ears of the Digital Twin, collecting data from multiple sources throughout the physical environment. These sensors include a wide range of devices and technologies that are strategically deployed to collect information on various parameters. For example, in cities, sensors may include cameras to monitor traffic flow and pedestrian movement, air quality monitors to measure pollution levels, temperature sensors to track urban heat island effects, noise detectors to identify noise pollution hotspots, and motion sensors to detect activity in public spaces. In addition, there are IoT-enabled devices embedded in infrastructure or worn by individuals, such as smart meters to monitor energy consumption or wearable devices to track health and fitness. This extensive network of sensors generates a continuous stream of data that provides valuable insights into various aspects of urban life, including transportation, energy use, environmental quality, waste management, and public health (Botín-Sanabria et al., 2022).

By integrating sensors into a Digital Twin, cities and organizations can gain a comprehensive, real-time understanding of their systems and environments. The digital representation serves as a mirror of the physical world, capturing the dynamic nature of the urban landscape. City planners, policymakers, and stakeholders can monitor key parameters and identify anomalies or trends as they occur, enabling proactive decision-making and responsive action. For example, by analyzing data from traffic sensors, city officials can optimize traffic flow, reduce congestion, and improve transportation infrastructure planning. Environmental sensors provide valuable information on air pollution levels, helping to develop strategies to improve air quality and public health. Noise detectors can identify areas with high noise levels, enabling targeted interventions to reduce noise pollution. Waste management systems can be optimized by using sensor data to monitor the level of waste bins, enabling efficient collection routes and reducing operating costs. In addition, integrating sensors into a Digital Twin enables predictive analytics and modeling capabilities. By analyzing historical and real-time data, organizations can create simulations and scenarios to understand the potential impact of various interventions or changes. City planners can simulate the impact of new building developments on energy consumption, assess the impact of changes to transportation systems on traffic patterns and emissions, or model the impact of extreme weather events on infrastructure resilience. These simulations enable decision makers to explore alternative scenarios, optimize resource allocation, and plan for future growth and sustainability. With the ability to predict and simulate outcomes, cities and organizations can make informed decisions, mitigate risks, and implement effective strategies to address complex challenges (White et al., 2021).

However, integrating sensors into a Digital Twin presents challenges that must be addressed for successful implementation. Data management and privacy concerns must be carefully addressed to ensure the safe and responsible handling of sensitive information. This includes consideration of data ownership, data security, and compliance with relevant regulations. Interoperability and standardization of sensor technologies and data formats are critical for seamless integration and data exchange between different systems and stakeholders. Establishing common protocols and frameworks enables interoperability, allowing sensors from different vendors to communicate and share data effectively. In addition, data governance frameworks and data sharing agreements facilitate collaboration among stakeholders while addressing privacy concerns (Qi et al., 2021).

In summary, the integration of sensors into Digital Twins has immense potential to drive urban development, industrial optimization, and infrastructure management. It provides organizations with real-time data that enables evidence-based decision making, efficient resource management, and improved quality of life for residents. By harnessing the power of sensors and Digital Twins, cities and industries can embark on a journey towards smarter, more resilient and sustainable environments.

2.3.1 API'S

APIs (Application Programming Interfaces) play a crucial role in the implementation and functioning of Digital Twins. APIs enable seamless communication and interaction between the Digital Twin and other systems, applications, or devices. Described below is an overview of the significance of APIs in the context of Digital Twins (Pedersen et al., 2021; Platenius-Mohr et al., 2020):

- Data exchange: APIs facilitate the exchange of data between the physical entity and its Digital Twin. Through well-defined API endpoints, data from sensors, devices, or other data sources can be captured and transmitted to the Digital Twin for real-time monitoring and analysis. Conversely, the Digital Twin can provide information and insights to external systems or applications through APIs.
- Real-time monitoring and control: APIs enable real-time monitoring and control of the physical entity through its Digital Twin. By integrating APIs with the Digital Twin, users can retrieve live data, monitor various parameters, and make informed decisions based on the insights provided by the Digital Twin. APIs also allow users to send commands or instructions to the physical entity, enabling remote control or automation of processes.
- Analytics and predictive capabilities: APIs in Digital Twins enable the integration of analytical tools and algorithms. Data collected from the physical entity can be processed, analyzed, and visualized through APIs, providing valuable insights into the current state, performance, and behavior of the entity. Additionally, predictive models can be built and integrated using APIs to forecast future behavior, optimize performance, or detect anomalies.
- Integration with external systems: APIs facilitate the integration of Digital Twins with other systems, platforms, or applications. By exposing APIs, Digital Twins can seamlessly exchange data and interact with enterprise systems such as asset management systems, ERP (Enterprise Resource Planning) systems, or maintenance management systems. This integration enables the Digital Twin to leverage existing data sources and streamline workflows across different domains.
- Collaboration and interoperability: APIs promote collaboration and interoperability between Digital Twins and diverse stakeholders. By providing standardized APIs, different parties involved in the lifecycle of a physical entity, such as designers, manufacturers, operators, or maintenance personnel, can access and interact with the Digital Twin, contributing their expertise and leveraging the Digital Twin's capabilities.
- Scalability and extensibility: APIs enable the scalability and extensibility of Digital Twins. New features, functionalities, or services can be added to the Digital Twin ecosystem by developing additional APIs. This allows the Digital Twin to evolve over time, accommodating new requirements, integrating with emerging technologies, or adapting to changing business needs.
- Security and access control: APIs in Digital Twins incorporate security mechanisms to ensure data protection, privacy, and access control. Authentication and authorization protocols can be implemented to authenticate users or systems accessing the Digital Twin's APIs, ensuring that only authorized entities can interact with the Digital Twin and its associated data.

In summary, APIs serve as the bridge between physical entities and their Digital Twins, enabling data exchange, real-time monitoring and control, analytics, integration, collaboration, scalability, and security. Through APIs, Digital Twins become powerful tools for simulation, analysis, optimization, and decision-making in various domains such as manufacturing, infrastructure management, healthcare, and more.

2.3.2 WFS SERVER

A Web Feature Service (WFS) is a standard protocol in geographic information systems (GIS) that allows users to retrieve and manipulate geospatial feature data over the Internet. It is a web-based data delivery mechanism that enables the exchange of vector-based geospatial information between servers and clients (Open Geospatial Consortium, 2023). WFS servers play a critical role in providing access to geospatial data stored in a variety of formats, including shapefiles, GeoJSON, GML, and more. These servers adhere to the specifications defined by the Open Geospatial Consortium (OGC), which ensures interoperability and compatibility between different GIS software and systems. WFS servers have become essential components in the distribution and use of geospatial data on the Web. They provide seamless access to geospatial features, facilitate data sharing and collaboration, and support the development of interoperable GIS applications across platforms. WFS servers in GIS, and therefore, Digital Twins provide several key features and functionalities (Peng & Zhang, 2004):

- Data Retrieval: Users can retrieve feature data from geospatial databases or sources by sending requests to WFS servers using standard web protocols. The server responds with the requested data in a specified format, such as HTTP or HTTPS.
- Query and filter: WFS servers support various query operations that allow users to filter and extract specific features based on attribute values or spatial criteria. Spatial queries (e.g., within a bounding box) and attribute queries (e.g., features with specific property values) are commonly used.
- Data transformation: WFS servers can perform on-the-fly data transformations, allowing clients to request data in different coordinate systems or projections. This capability ensures seamless integration and display of data in the desired coordinate reference system.
- Data Updates: In addition to supporting data retrieval, WFS servers also support data modification. Users can add, update, or delete features in the server's database by making appropriate requests. This functionality facilitates collaborative data editing and maintenance.
- Security and access control: WFS servers can implement security measures to control access to sensitive data. Authentication and authorization mechanisms can be used to restrict access to specific users or user groups, ensuring data privacy and preventing unauthorized changes.
- Metadata and Cataloging: WFS servers provide metadata descriptions of available data sets, including information about feature types, attributes, and data sources. This metadata facilitates the discovery and cataloging of geospatial resources.
- Integration with other Web services: WFS servers can be seamlessly integrated with other Web services that conform to Open Geospatial Consortium (OGC) standards, such as Web Map Service (WMS) and Web Coverage Service (WCS). This integration allows clients to retrieve and combine different types of geospatial data from multiple sources.

Overall, WFS servers serve as powerful tools for data retrieval, querying, transformation, updating, security, metadata management, and integration, thereby enhancing the accessibility and utility of geospatial data in GIS applications.

2.3.3 CONCLUSION

The integration of sensors into Digital Twins has transformed planning, management, and sustainability in various domains. Sensors act as the eyes and ears of Digital Twins, collecting real-time data and enabling informed decision-making. Integrating sensors into digital representations provides organizations with a real-time understanding of their systems and environments. Cities deploy sensors to monitor traffic flow, air quality, temperature, noise levels, etc. This data optimizes transportation, improves air quality, reduces noise pollution, and enhances waste management. Sensors integrated into Digital Twins enable predictive analytics and modeling, facilitating simulations to understand the impact of interventions or changes and plan for future growth and sustainability. However, challenges such as data management, privacy, interoperability, and security must be addressed. Common protocols, frameworks, and data governance frameworks promote collaboration and ensure responsible handling of sensitive information.

APIs are crucial for Digital Twins, enabling data exchange, real-time monitoring and control, analytics, integration with external systems, collaboration, scalability, and security. APIs serve as bridges between physical entities and their Digital Twins, empowering simulation, analysis, optimization, and decision-making in various domains.

Web Feature Service (WFS) servers, standard protocols in GIS, provide seamless access to geospatial features, support data retrieval, query and filter operations, data transformations, data updates, security measures, metadata management, and integration with other web services. WFS servers enhance the accessibility and utility of geospatial data in GIS applications, playing a critical role in Digital Twins.

In conclusion, integrating sensors into Digital Twins, supported by APIs and WFS servers, drives urban development, industrial optimization, and infrastructure management. It enables evidence-based decision-making, resource optimization, and improved quality of life. Careful attention must be given to data management, privacy, interoperability, and security to ensure successful implementation.

2.4 DIGITAL TWINS IN THE URBAN SPACE

Research by Lehtola et al. (2022) states that in construction, Digital Twins provide similar benefits by incorporating information about the physical landscape of a building into the design process. Facility management also benefits economically from Digital Twins, but they require regular updates. Urban Digital Twins introduce additional complexity, both in terms of technical issues, such as the integration of GIS and BIM data, and human factors, such as the uncertain purpose of urban Digital Twins. For example, different stakeholders such as city officials, architects, engineers, and community members may have different goals and perspectives when it comes to urban planning using Digital Twins (Liu et al., 2022). Technical interoperability can support co-creation, management, and data sharing among stakeholders, and clear communication can support fair decision-making processes (Turk, 2020). Digital twins representing the city can provide reliable information to test scenarios, such as disaster preparedness. Additionally, Choi, Al-Hussein, & Lee (2019) state that Digital Twins can be used to improve coordination and collaboration between different stakeholders in the construction process, leading to fewer errors and better project outcomes. Mbohwa, Chinyio, & Ojiako, (2018) show that Digital Twins can also be used to facilitate the integration of smart technologies in the built environment, enabling more efficient and responsive building operations, which can lead to improved energy efficiency, occupant safety, and overall sustainability of buildings and infrastructure.

The Digital Twin of a city is a collection of interconnected digital representations of various aspects of the city's infrastructure and functions. These Digital Twins are constantly updated with real-time data from different sources, allowing for fine-tuning and synchronization with the actual state of the city (Ruohomaki et al., 2018). The effective functioning of a city's Digital Twin depends on a constant flow of data from different sources within the city's digital infrastructure. Ivanov et al. (2020) highlight the following examples as sources for a city's Digital Twin:

- The mobility data of city residents, including information about private, commercial, and public transportation, as well as traffic congestion, is collected through various mechanisms, such as single travel card transactions and traffic monitoring. The OV-chipkaart in the Netherlands is an example of a single travel card because it can be used for all modes of public transportation in the Netherlands.
- The physical parameters of the urban environment, including air temperature and humidity, air particles and chemical composition, noise pollution, radiation levels, and water chemical composition, can be monitored and analyzed in real time using smart sensors. These sensors are linked to the geographic location of the city.
- Data from outdoor surveillance cameras can be used to intelligently analyze characteristics of the urban environment that are difficult or impossible to collect by other means, such as traffic congestion, pollution, and the quality of the road network.
- In addition, open source data from sources such as government portals, meteorological services, and business entities can be used to improve models for intelligent data analysis.

The data sources mentioned by Ivanov et al. (2020) can provide the functionality of specific Digital Twins, such as a Digital Twin for Urban Infrastructure, which represents an interactive 3D model of urban infrastructure, as well as buildings, structures, and engineering communications. Another possibility is a Digital Twin for a city's transportation network. This Digital Twin can be used to monitor and predict the availability of transportation, or to show the efficiency of public transportation. A third example can be a Digital Twin for urban ecology, which can provide insights into the environmental conditions of the urban environment, such as the quality of soil, water, air, etc. These Digital Twin capabilities can help cities to:

- Control air and noise pollution through real-time environmental monitoring using various sensors.
- Improve traffic flow with dynamic traffic lights and markings based on camera monitoring.
- Monitor the wear and tear of roads and bridges, and provide timely maintenance.
- Control energy consumption of street lights by turning them off when not needed.
- Implement on-demand garbage collection using real-time sensors.

The use of Digital Twins in the built environment also raises some challenges and concerns. One major challenge is the need for accurate and up-to-date data to create and maintain Digital Twins (Ong et al., 2018). This requires the integration of different data sources, including sensors, building information models (BIM), and other information sources. Another challenge is the need for robust and secure data management systems to store and process the data used by Digital Twins (Choi et al., 2019). This includes ensuring data privacy and security, as well as addressing concerns about the potential misuse of data collected from Digital Twins.

In conclusion, Digital Twins have the potential to improve the design, construction, and operation of buildings and infrastructure in the built environment. However, these benefits can only be realized if challenges related to data accuracy, integration, and management are addressed.

2.4.1 EXAMPLES OF DIGITAL TWINS FOR CITIES AROUND THE WORLD

To give an idea of how the above theory is put into practice, this section presents some examples of cities around the world that have developed a Digital Twin to varying degrees and for different use cases.

ZURICH'S DIGITAL TWIN

A great example of the use of a Digital Twin in urban planning is the example described by Schrotter & Hürzeler (2020) using the city of Zurich. The Digital Twin is used to replace old, traditional, static methods and tools used in the planning process of the urban environment. This digital transformation in planning and decision making can result in processes that are more illustrative, easier to understand and more comprehensible. The Digital Twin of the City of Zurich is an important data source for these processes, as it transforms the physical elements of the city, such as buildings and vegetation, into the digital world. This digital representation can be updated as needed, providing benefits in the digital space. By making this data available through Open Government Data, it can be used to develop applications, promote understanding, and support the creation of collaborative platforms. The Digital Twin can also be used to visualize and analyze scenarios, allowing them to be developed digitally and discussed in decision-making bodies. It can be used to simulate the urban climate and link the results to existing 3D geospatial data. The 3D geospatial data, models and metadata must be carefully managed and updated as needed to support decision making in an understandable way (Stadt Zürich Geomatik + Vermessung Geodaten, 2022). Figure 2 shows the use of the Digital Twin for noise pollution and solar potential.

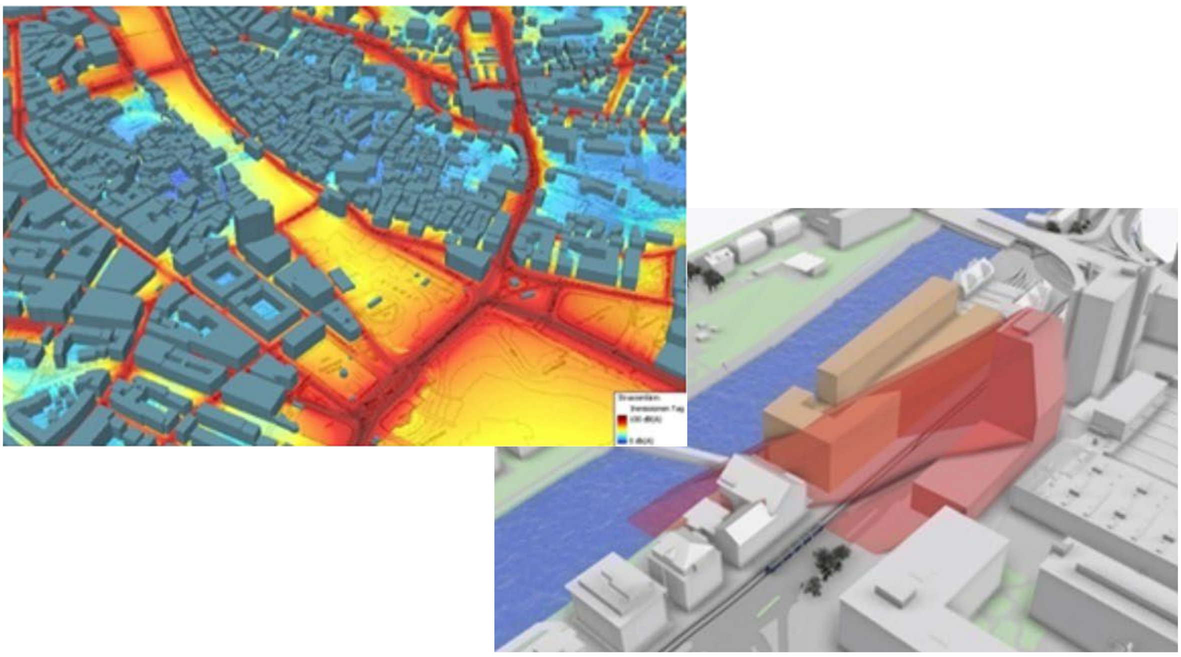

Figure 2 Applications of Zurich's Digital Twin - Noise pollution & Solar Potential | Source: Stadt Zürich Geomatik + Vermessung Geodaten (2022)

The example of Schrotter & Hürzeler (2020) briefly explains the steps taken to develop the Digital Twin for the city of Zurich. In 2007, they started to model the 3D spatial data of the city using the digital terrain model (LoD0), the block model (LoD1), and the roof model (LoD2), where LoD stands for Level of Detail. The terrain model is generated from LIDAR images with a resolution of 50 cm, and the block model is based on real & planned building ground plans, which have an average position error of 10-15 cm, while the average height error is around 50 cm. The roof model is generated from semi-automatic stereo aerial photogrammetric processing with an average position error of 10-15cm and an average height error of about 20cm. The three models are continuously updated. Figure 3 shows the 3D spatial model based on the terrain, block and roof models.

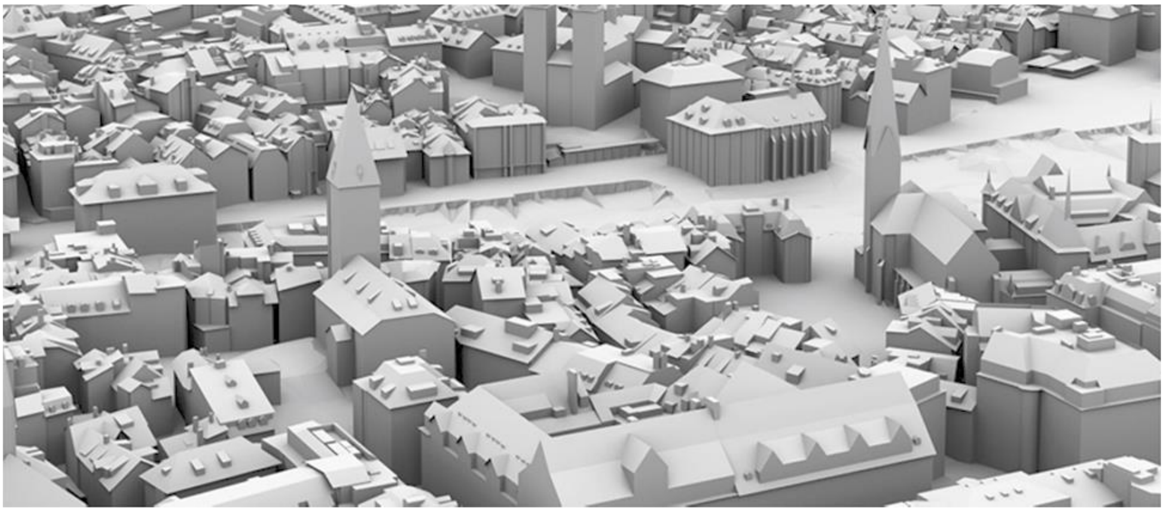

Figure 3 The 3D Spatial model (LoD1, 2 & 3 combined) | Source: Stadt Zürich Geomatik + Vermessung Geodaten (2022)

The characteristics of spatial data are formally described by metadata, which includes information about the origin, structure, content, validity, timeliness, rights of use, accuracy, processing methods, or access options. Without this metadata, it is impossible to derive valid decisions and actions from the spatial data. In addition to this metadata, the lifecycle of spatial data is described so that physical entities such as roads can be digitally planned and maintained based on defined intervals. Rapidly changing entities can contain time-critical information using real-time sensors. Since July 2013, they have integrated 2D pipelines and cables to provide underground infrastructure data in the Digital Twin. They have also added other infrastructure elements such as bridges, trees, and power lines.

SINGAPORE

Singapore has completed the world's first Digital Twin of an entire nation, helping the country respond to challenges such as the effects of climate change and the adoption of renewable energy. The Digital Twin replicates the real world through intense digitalization and requires a sophisticated data management platform to constantly update the data. A single source of truth across multiple Digital Twins is essential for long-term, resilient, and intelligent development. However, creating maps in a way that respects the privacy of citizens, the confidentiality of enterprise data IP, and the security of the underlying data is challenging. The partnership with Bentley Systems helped Singapore implement a "capture once, use by many" strategy that maximized accessibility to the map by making it available as an open source 3D national project map for collaboration among government agencies, authorities, and consultants (Lawton, 2022).

Singapore has made significant progress in implementing Digital Twin technology and is considered a leader in the field. The country's Digital Twin initiative involves creating a virtual replica of the city-state by integrating real-time data, analytics, and visualization tools. Singapore's Digital Twin aims to support urban planning, infrastructure development, and smart city initiatives.

The journey began with the Singapore National 3D Mapping project, which aimed to map the entire country with accurate and reliable 3D data. This involved mobile aerial and road mapping using laser scanners and cameras mounted on aircraft and vehicles. The core geospatial data produced is shown in Figure 4 and includes terrain models, building models, orthophotos, imagery and point clouds.

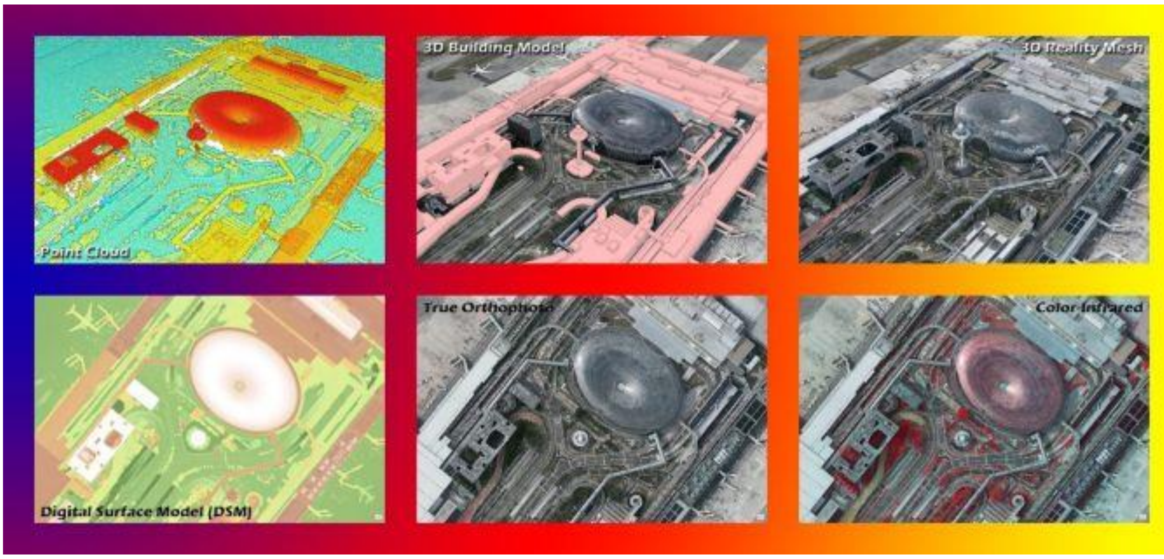

Figure 4 National 3D Mapping of Singapore using different geodata types | Source: GIM (2023)

To handle the massive amount of geospatial data, Singapore adopted commercially available software-as-a-service (SaaS) solutions. The data management platform enables data sharing with other users and supports the long-term sustainability of the mapping program and Digital Twin.

Singapore is also working to map underground infrastructure to optimize land use and minimize disruption. The Digital Underground project aims to develop a reliable map of underground utilities, and the Singapore Land Authority (SLA) has partnered with the City of Zurich and the Singapore ETH Center.

To ensure up-to-date geospatial data, Singapore has established a mapping program for continuous data collection and is exploring rapid mapping technologies such as lidar and AI-based 3D modeling. The goal is to map the nation every five years using aerial mapping and to update mobile road mapping data every two years.

The gap between 2D and 3D geospatial data is recognized, and efforts are underway to bridge the gap in standards, governance, data models, formats, and visualization. Geospatial professionals play a critical role in driving the adoption of Digital Twins by providing high quality and reliable 3D data.

Singapore sees Digital Twins as the foundation for future cities and envisions their use in emerging technologies such as AI, IoT, virtual reality (VR), and augmented reality (AR). The country is encouraging other national mapping and geospatial agencies to develop and maintain authoritative 3D city models.

Overall, Singapore's Digital Twin journey is characterized by a commitment to sustainable systems, long-term planning, and the availability of skilled geospatial professionals. The Digital Twin concept has been instrumental in various applications, including urban planning, wind simulations (Figure 5), flood risk management, energy optimization, aviation safety, and asset management (Van Wegen, 2023).

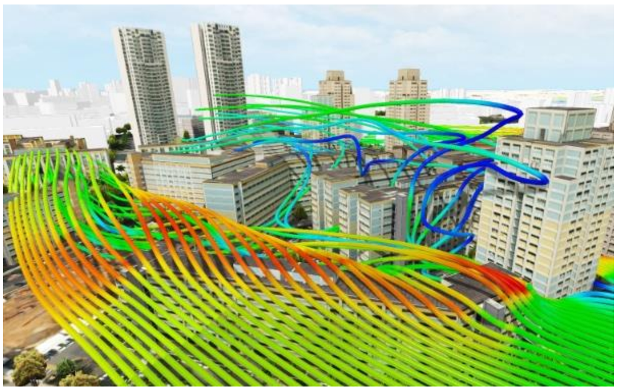
Figure 5 Wind simulation Singapore | Source: (Sacyr, 2021)

XIONG'AN

Xiong'an New Area is a planned economic zone in China, located southwest of Beijing. It is envisioned as a model city that integrates advanced technologies and sustainable development principles. As part of this vision, the concept of a "Digital Twin" has been applied to Xiong'an.

In the case of Xiong'an, the Digital Twin aims to create a comprehensive and dynamic representation of the entire city. It leverages various technologies, including big data, artificial intelligence (AI), Internet of Things (IoT), and cloud computing, to collect, analyze, and visualize real-time data about the city's infrastructure, environment, and operations.

Xiong'an Digital Twin is designed to serve multiple purposes. First, it enables city planners and policymakers to have a holistic view of the city, allowing them to make informed decisions about urban development, resource allocation, and infrastructure planning. By simulating different scenarios and predicting their outcomes, the Digital Twin can help optimize city management and improve efficiency.

Second, the Digital Twin facilitates citizen engagement and participation. It provides a platform for residents to access information about the city, such as transportation schedules, environmental data, and public services. Citizens can use this information to make informed decisions and actively contribute to the city's development. The Digital Twin also enables the government to collect feedback and suggestions from the public, promoting a more inclusive and participatory approach to urban governance.

In addition, Xiong'an's Digital Twin supports the implementation of smart city initiatives. It enables the integration of various urban systems, such as transportation, energy, water management, and public safety, into a unified platform. This integration allows for real-time monitoring, analysis, and optimization of these systems, leading to improved urban sustainability, resource efficiency, and quality of life for residents (Stokols, 2023).

HELSINKI

Helsinki, the capital city of Finland, has been at the forefront of using digital technologies to improve urban planning and development. One notable initiative is the creation of Helsinki's Digital Twin, which aims to provide a comprehensive and dynamic virtual representation of the city.

Helsinki's Digital Twin is a virtual representation of the city that combines IT services, open data and information to provide an overview of the city's environment and functionality. The Digital Twin enables the city to know what is happening in real time, predict the future and prepare for unforeseen situations, and provide more targeted services to citizens. Helsinki's 3D city models are an integral part of the Digital Twin, which helps simulate and analyze situations and supports innovation and research through data sharing. Building the Digital Twin requires long-term collaboration within the city organization, and the use of new technologies such as AI and game engines is constantly changing the technical body and use cases of the Digital Twin (Helsinki's Digital Twin and City Models, 2023).

AMSTERDAM & UTRECHT

Amsterdam and Utrecht have developed a platform that can be used free of charge by all municipalities and other government agencies in the Netherlands. The platform enables municipalities to move from 2D to 3D processing of information, which is necessary to comply with environmental legislation and to address complex issues such as housing, mobility and climate change. The 3D gaming platform enables municipalities to visualize and model existing situations and, in addition, use the data provided by 3D modeling to reduce costs and improve communication with stakeholders. The platform also provides an opportunity for internal GIS/GEO departments to gain experience in 3D modeling and for designers and developers to add models to the platform (Digital Twin Voor Alle Gemeenten | VNG, 2022).

2.4.2 EXAMPLES OF DIGITAL TWINS FOR PORTS AROUND THE WORLD

The digitalization of core port activities includes several relevant projects. HaMIS is a central system for managing, guiding and inspecting visiting vessels, facilitating the exchange of information and reducing the administrative burden. PortMaps provides a digital geographic map of the Port of Rotterdam and access to relevant information about specific locations. Smart Infra involves equipping infrastructure with sensors and data communication to optimize design, maintenance and commercial agreements. The Floating Lab is a test vessel equipped with cameras, measurement equipment and sensors to develop and test smart shipping and autonomous navigation applications.

Portbase, a joint venture between the Port of Rotterdam and the Port of Amsterdam, serves as the digital hub for the Port of Rotterdam. It provides a port communication system that enables automated data exchange for various notifications and declarations between companies and government agencies. The system's multiple applications allow data to be reused, reducing errors and minimizing administrative work. Portbase ensures that core processes in all Dutch ports are in order, facilitating paperless transactions and digital data exchange. The data and coverage of the Port Communication System are valuable for logistics improvement and innovation. Portbase enables companies to use the data, with the owner's permission, to develop new solutions. The national coverage of the system and the existing connections provide maximum reach for innovative logistics solutions. Furthermore, Portbase promotes the Netherlands as an appealing logistics data hub for international players looking to conduct business in and through the country.

Autonomous navigation is a future goal, and all the projects mentioned above contribute to the ambition of enabling autonomous navigation in the Port of Rotterdam by 2030. The development of a Digital Twin of the port, including infrastructure, vessel movements, weather conditions and hydro-information, plays a crucial role. An IoT cloud platform, developed in collaboration with IBM, Esri, Cisco and Axians, collects and visualizes hydro and meteorological data through sensors. This platform helps reduce waiting times, optimize berthing, loading, and departure times, and predict the best time to dock and depart based on water levels, currents, and wind conditions (Port of Rotterdam, n.d.).

OTHER PORTS

Several ports around the world are using Digital Twin technology to improve their operations. The Port of Montreal uses a virtual simulation, or Digital Twin, to train new employees in port security. This simulation allows employees to experience potential accidents and disruptions in a safe environment. The Digital Twin also helps ports operate their businesses by enabling them to make smarter, faster, and safer decisions. Digital twin technology can benefit ports in many ways beyond training new employees. The Port of Hamburg is using augmented reality and 5G technology to streamline processes, while the Port of Singapore has a Center for Excellence in Modeling and Simulation of Next Generation Ports to improve operational efficiency. The Port of Barcelona is monitoring port operations and using the data for analysis and decision-making (PierNext, 2020).

2.4.3 CONCLUSION

In summary, cities around the world are embracing the concept of Digital Twins to improve urban planning and development. Zurich's Digital Twin replaces traditional planning methods with a more illustrative and comprehensive approach, providing benefits in the digital space and supporting collaborative platforms. Singapore has completed the world's first Digital Twin of an entire nation, enabling sustainable and resilient development while maximizing data accessibility. Xiong'an, a planned economic zone in China, is using a Digital Twin to optimize city management, engage citizens, and integrate smart city initiatives. Helsinki's Digital Twin provides real-time insights, predictive capabilities, and targeted services to improve city functionality and citizen services. Amsterdam, Utrecht, and the Port of Rotterdam in the Netherlands have also adopted Digital Twin platforms to improve information processing, visualization, and stakeholder communication. In addition, ports around the world, including Montreal, Hamburg, Singapore, and Barcelona, are using Digital Twins for training, operational efficiency, and decision-making. These examples demonstrate the broad applications and benefits of Digital Twins in urban environments.

2.5 RESEARCH GAP

The concept of Digital Twins has received considerable attention in various industries and applications due to its potential benefits. However, several research gaps remain to be addressed in future research in order to fully exploit the capabilities of Digital Twins:

One of the major research gaps is the lack of standardized frameworks for implementing and operating Digital Twins. While there is existing literature discussing different levels and capabilities of Digital Twins, a comprehensive framework is needed to guide organizations in developing and deploying Digital Twins effectively. Standardization efforts can establish best practices, promote interoperability, and ensure consistency across industries and applications.

Another critical area of research is the integration of sensor data into Digital Twins. Sensors play a critical role in collecting real-time data and enabling informed decision making. However, research is needed on how to effectively integrate different sensor technologies, data formats, and data management processes into Digital Twins. This research should focus on addressing challenges related to data interoperability, quality assurance, privacy, and security.

The integration of sensors and real-time data collection in Digital Twins raises concerns about privacy and ethical considerations. Research should address these concerns by exploring methods for ensuring data privacy and security, establishing ethical guidelines for data use, and developing frameworks for responsible data governance. This includes addressing issues such as data ownership, consent, transparency and accountability.

As Digital Twins grow in size and complexity, their scalability and sustainability become important considerations. Research is needed to explore approaches for managing large-scale Digital Twins, such as citywide or nationwide implementations, and ensuring their long-term viability. This includes managing the computational and storage requirements of large-scale Digital Twins and ensuring their resilience to technological advances and evolving user needs. Understanding human factors and engaging stakeholders are critical to successful Digital Twin implementations. However, there is limited research on the social aspects of Digital Twins, including understanding stakeholder perspectives and goals, facilitating collaboration, and ensuring inclusive decision-making processes. Research should explore methods and frameworks for effectively engaging stakeholders in the design, implementation, and use of Digital Twins.

There is also a need for robust validation and evaluation methods to assess the performance and effectiveness of Digital Twins. Research should focus on developing standardized methodologies to validate Digital Twins against their physical counterparts and to assess their impact on decision making, efficiency gains and sustainability outcomes. These methodologies should take into account technical aspects as well as the socio-economic and environmental dimensions of Digital Twins.

Addressing these research gaps can facilitate the further development and wider adoption of Digital Twins, unlocking their full potential in areas such as urban planning and management of environmental entities of the public space.

2.6 CONCLUSION

Digital Twins, which are digital representations of physical assets, have gained popularity in various fields with advances in technology. The concept of Digital Twins originated in the aerospace industry but has since been applied in areas such as product manufacturing and smart cities. A Digital Twin consists of physical components, virtual models, and the data that connects them, enabling the virtual assets to use embedded engineering and AI for managing the physical asset.

Digital Twins can be leveraged at different levels of sophistication. Level 1 involves creating a virtual prototype during the design process to identify and mitigate technical risks. Level 2 incorporates real-time performance and maintenance data from the physical twin, allowing for high-level decision-making and exploration of different scenarios. Level 3 and Level 4 Digital Twins introduce adaptive and intelligent capabilities, respectively, with machine learning algorithms and autonomous analysis to support real-time planning and decision-making.

In the urban space, Digital Twins offer numerous benefits. They can incorporate information about the physical landscape of buildings into the planning process, improve coordination and collaboration among stakeholders in construction projects, and facilitate the integration of smart technologies for efficient building operations. Urban Digital Twins require the integration of various data sources, including sensors, Building Information Models (BIM), and other information sources. They can provide insights into environmental conditions, enable real-time monitoring and control of air and noise pollution, improve traffic flow, monitor infrastructure wear and tear, and optimize energy consumption.

Several examples of Digital Twins in cities and ports worldwide demonstrate their practical implementation. For instance, the City of Zurich developed a Digital Twin to transform physical elements into the digital world, enabling visualizations, analysis of scenarios, and simulation of the urban climate. Singapore has created the world's first Digital Twin of an entire nation, helping the country address climate change and renewable energy challenges. These examples showcase the importance of accurate and up-to-date data, metadata management, and the integration of various infrastructure elements and sensors. Integrating sensors into a city's Digital Twin improves urban planning, management, and sustainability. Real-time data collected and analyzed by sensors enables informed decision-making and improves the quality of life for residents. Sensors collect data from multiple sources, providing insights into urban life. This integration facilitates a comprehensive understanding of the environment, optimizing resource allocation and future planning. Challenges in data management, privacy, and interoperability must be addressed. Despite these challenges, sensor integration enables cities to become smarter, more resilient, and sustainable, benefiting the urban environment.

However, the use of Digital Twins in the built environment comes with challenges. Ensuring data accuracy, integration, and management is crucial. Robust and secure data management systems are necessary to handle large volumes of data and address privacy and security concerns. Additionally, the development and maintenance of Digital Twins requires ongoing efforts to update models and incorporate real-time data. In conclusion, Digital Twins have the potential to revolutionize urban planning, construction, and infrastructure management. By creating digital representations of physical assets and integrating real-time data, municipalities can make informed decisions, optimize resource utilization, and improve the overall efficiency, sustainability, and resilience of urban environments.

Through this literature review, three of the questions mentioned in Section 1.3 can be answered, namely what a Digital Twin is, its applications in urban space, and the sensor data that can be included, we have gained a comprehensive understanding of the concept and its importance. A Digital Twin is a digital representation of a physical asset that enables the integration of real-time data and advanced analytics. In the urban space, Digital Twins are used for a variety of purposes, including enhancing stakeholder coordination, optimizing resource allocation, and facilitating the integration of smart technologies. Sensor data plays a critical role in Digital Twins as it can provide insights into environmental conditions, air and noise pollution, traffic flow, infrastructure status, and energy consumption. Integrating sensor data into urban Digital Twins enables real-time monitoring, analysis, and control, supporting informed decision-making and improving the quality of life for residents.

To answer the remaining sub-questions defined in Section 1.3, interviews are conducted and practical insights are generated. By incorporating first-hand knowledge and industry perspectives, these approaches provide valuable real-world examples and experiences. They help refine frameworks, address challenges, and improve stakeholder engagement. Integrating practical knowledge and industry expertise effectively bridges the gap between theory and application, facilitating the advancement and wider adoption of Digital Twins.

3 MUNICIPALITY INSIGHTS INTO DIGITAL TWINS

Municipalities in the Netherlands are required by law (Wet basisregistratie grootschalige topografie) to keep track of certain geographical data (Overheid, 2022). This law results in all municipalities having a collection of 2D data of their environmental entities in the public space, including data on objects such as roads, bridges, sewers, waterways, railway lines, and more. However, municipalities collect and manage this data in their own way. They use specific workflows and collect additional data using sensors.

To get a better understanding of these workflows, a pilot area in the municipality of Weert is used to see what data is used and how. In addition, interviews will be conducted with managers of the municipality of Weert who are responsible for the management of the environmental entities of the public space. These interviews will provide a better understanding of their processes and data collection. Due to the scope of the research, the interviews are only conducted with individuals from the municipality of Weert. This chapter first introduces the pilot area and the interviewees and then describes the questions asked during the interviews. The results of the interviews are then discussed and concluded in sections 3.4 and 3.5.

3.1 PILOT AREA

To thoroughly test the capabilities of the framework, a diverse area of interest is required that includes many physical entities from different management types. Therefore, in consultation with the municipality of Weert, the area of interest is the neighborhood of Molenakker, indicated by the striped line in Figure 6.

Molenakker is a relatively new neighborhood, built in the 1990s and 2000s. The area consists mainly of low-rise housing, with some apartment buildings and townhouses. It also features several large parks and playgrounds, as well as large bodies of water. In terms of amenities, Molenakker has a small shopping center with a supermarket and a few other shops, as well as three primary schools and a community center.

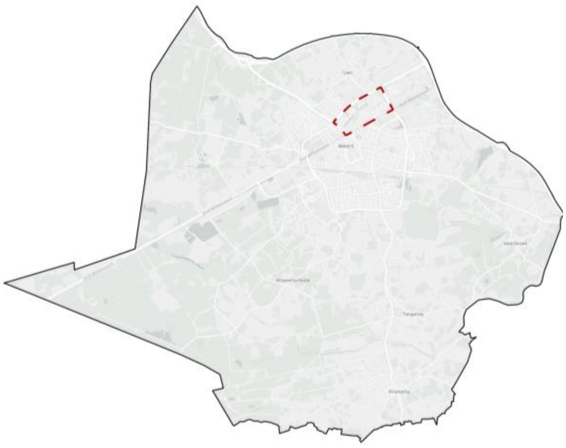

Figure 6 Location of Molenakker in Weert.

Molenakker serves as an excellent pilot area for the implementation of a Digital Twin due to several factors:

- Urban setting: Molenakker represents a typical urban neighborhood with a mix of residential, commercial and public spaces. It provides a microcosm of the urban environment, allowing for a focused and manageable scope for implementing and testing Digital Twins.
- Diversity of infrastructure: The neighborhood includes a variety of infrastructure elements such as buildings, streets, green spaces, and utilities. This diversity allows for the integration of different data sources and sensors to capture and monitor different aspects of urban life.
- Scalability and replicability: Molenakker's characteristics and size make it scalable and replicable in other neighborhoods and cities. Lessons learned from implementing Digital Twins in Molenakker can be applied to similar urban areas, facilitating wider adoption and implementation of the technology.

By using Digital Twins in the Molenakker neighborhood, managers can gain valuable insights into urban processes, optimize resource allocation, improve infrastructure planning, and enhance the quality of life for residents. The localized focus allows for a comprehensive understanding of the dynamics of the neighborhood, making it an ideal pilot area to test and refine Digital Twin technologies for broader citywide applications.

3.2 INTERVIEWEES

The municipality of Weert, like most other municipalities in the Netherlands, has several teams that are responsible for managing the environmental entities in the public space. In Weert, these are divided into Water & Sewerage, Road Infrastructure, Green & Waste, Parking and Technical Installations. Several people from each team are interviewed. This results in the list of interviewees in shown Table 1.

Table 1 List of interviewees

Team	Job titles
Water & Sewerage	Program director Water & Sewerage Functional manager Water & Sewerage
Road Infrastructure	Program director Road infrastructure Functional manager Road infrastructure Director Road infrastructure
Green & Waste	Program director Green & Waste Functional manager Green Functional manager Waste Director Green
Parking	Program director Parking
Technical Installations	Functional manager Technical Installations

3.3 SETUP

The interviews are conducted during the week of March 20th in agreement with the head of the department "Public Space". The interviews took between 15 and 30 minutes and started with a short introduction of Digital Twins for the management of environmental entities, and in addition, a short presentation of a small example model of the pilot area of Weert is given (a very early version of the model shown in Chapter 6). After the introduction, the following questions are asked while creating space for discussion. The answers to these questions can be found in Appendix I.

1. What is your role within the municipality of Weert?
2. What data do you manage/are you responsible for?
3. Where is this data stored and in what format?
4. What tools do you use to manage/view this data?
5. What tasks do you perform to manage the data with these tools?
6. Are you using sensors to collect additional data in real time?
7. If so, what tool do you use to query this data?
8. Would you benefit from having at-a-glance access to data from other teams as well as your own?
9. Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?
10. What additional expectations do you have of a Digital Twin for public space management?

3.4 RESULTS

The municipality of Weert has identified several requirements and wishes from stakeholders regarding Digital Twins for cities. These requirements highlight the need for improved maintenance planning, efficient decision making and better use of resources. Let's take a closer look at each point and explain why it is needed, how it can be achieved and why a Digital Twin is the ideal solution:

1. Predict future maintenance needs based on historical data and current conditions:
A Digital Twin enables the integration of historical data and real-time conditions to predict future maintenance needs. By analyzing data from multiple sources, such as maintenance records, sensor data, and environmental factors, cities can proactively plan and schedule maintenance activities. This helps optimize resource allocation, reduce downtime, and ensure the longevity and functionality of city infrastructure.

2. Easily edit environmental entities, but be able to undo or reject changes:
Digital Twins provide a user-friendly interface for editing and manipulating the digital representation of the urban environment. Stakeholders can easily make changes, experiment with different scenarios, and visualize potential outcomes. The ability to undo or reject changes ensures that changes are carefully reviewed and approved before implementation in the physical world. This feature promotes efficient decision-making, minimizes risk, and maintains data integrity.

3. Determine the open space profile for heavy haul:
Using topographic data, infrastructure dimensions, and traffic requirements, Digital Twins can accurately determine the profile of open space for heavy traffic. This information is useful for route planning, ensuring adequate clearance for large vehicles, and preventing accidents or damage to infrastructure. By visualizing the open space profile, cities can make informed decisions about urban design and optimize traffic flow.

4. Visualize historical locations of sensors and their data:
Digital Twins enables the visualization of historical sensor locations and their associated data. This feature allows stakeholders to analyze patterns and trends in historical sensor data, helping them to understand the evolution of environmental conditions over time. By visualizing sensor data, cities can make informed decisions about infrastructure planning, environmental management, and urban development.

5. Calculate and visualize water on roads due to heavy rainfall:
Digital Twins, combined with weather data and topographic information, can accurately calculate and visualize water accumulation on roads during heavy rainfall. This capability supports flood management, infrastructure design, and emergency response planning. By understanding the potential water flow and impact, cities can implement preventive measures, optimize drainage systems, and ensure the safety and functionality of roads during adverse weather conditions.

6. Visualize and predict vegetation growth and its impact on the streetscape, cables, and pipes:
Digital Twins can simulate and visualize the growth of vegetation over time, taking into account factors such as climate, sun exposure, and soil conditions. This feature helps stakeholders understand the impact of vegetation growth on the streetscape and cables and pipes. By visualizing vegetation growth patterns, cities can plan for appropriate maintenance, prevent damage to infrastructure, and optimize the aesthetic appeal of urban spaces.

7. Verify collisions between existing environmental features and new proposed features such as trees and streetlights:
Digital twins allow stakeholders to identify and prevent collisions between existing environmental features and new proposed features. By simulating and visualizing proposed changes within the digital model, cities can identify potential conflicts prior to implementation in the physical environment. This capability ensures efficient urban planning, minimizes risks during construction, and enhances safety and functionality.

8. Visualize and consult citizen reports on public space issues and use them to identify problem areas through analysis:
Digital Twins provide a platform to integrate resident reports and feedback on public space issues. By analyzing this data in the context of the digital model, cities can identify problem areas, prioritize maintenance or improvement projects, and increase citizen engagement. The visualization of citizen reports helps stakeholders gain a comprehensive understanding of public space issues, ensuring effective problem solving and community satisfaction.

9. Advise on renovation projects based on standardization in process and materialization:
Digital Twins facilitate the standardization of retrofit processes and materials by providing a centralized platform for storing and linking relevant information. By leveraging this standardized knowledge base, cities can provide informed advice on renovation projects, ensure consistency in processes and material choices, streamline operations, and optimize resource utilization. This capability promotes efficient and cost-effective urban rehabilitation and maintenance.

10. Link documents to objects in the model:
Digital twins allow stakeholders to associate relevant documents and metadata with specific objects within the model. This functionality allows for centralized storage and easy retrieval of essential information related to urban assets and infrastructure. By associating documents with objects, cities can maintain an organized and comprehensive digital record, ensuring transparency, accountability, and efficient decision-making.

11. Predict the frequency of garbage collection using sensors:
By integrating sensor data from trash cans and collection vehicles into the Digital Twin, cities can predict the optimal frequency of trash collection. This predictive capability helps optimize waste management operations, reduce costs, and improve the cleanliness and livability of urban areas. Using real-time data from sensors, cities can dynamically adjust collection schedules based on actual bin levels, ensuring efficient resource allocation.

12. Predict parking occupancy under different conditions:
Digital Twins can incorporate data from parking sensors and relevant factors such as events, weather conditions, and time of day to predict parking occupancy. This predictive capability helps cities optimize parking management, improve traffic flow, and reduce congestion. By accurately predicting parking availability, cities can guide drivers to available spaces, reduce unnecessary traffic, and improve overall urban mobility.

13. Visualize renovations or new projects in the current state of the public realm:
Digital twins allow stakeholders to visualize proposed renovations or new projects in the context of the current state of the public realm. By overlaying digital representations on the existing environment, cities can assess the visual impact, functionality, and compatibility of new developments. This visualization capability supports effective urban design, public space management, and community engagement.

14. Predict or recommend maintenance activities based on a combination of historical maintenance data, materials, and sensor readings:
By combining historical maintenance data with information on materials, and sensor readings, Digital Twins can predict or advise on optimal maintenance actions. This predictive capability helps cities optimize maintenance schedules, allocate resources efficiently, and extend the life of city assets. By leveraging historical data and advanced analytics, Digital Twins provide valuable insights for proactive and data-driven maintenance planning.

In summary, the Digital Twins for cities can meet the needs and desires of the City of Weert by providing a comprehensive and interactive platform to address urban planning, maintenance, and decision-making challenges. By leveraging real-time data, advanced analytics, and visualization capabilities, Digital Twins enables stakeholders to make informed decisions, optimize resource utilization, and create sustainable and livable urban environments. The integration of multiple data sources and the ability to simulate and predict scenarios make Digital Twins the ideal solution for improving the efficiency, resilience, and sustainability of cities.

3.5 CONCLUSION

In conclusion, the municipality of Weert in the Netherlands is exploring the use of Digital Twins for the management of environmental entities in the public space. The pilot area chosen to test the capabilities of the framework is the neighborhood of Molenakker. This neighborhood offers a variety of infrastructure elements that make it suitable for implementing and testing Digital Twins.

In order to gain insight into the workflows and data collection processes, interviews were conducted with various managers responsible for the management of various environmental units in the municipality of Weert. The interviews provided valuable information about their roles, data management practices, tools used, and the potential benefits of implementing Digital Twins in their work.

The municipality of Weert identified several requirements and desires for Digital Twins in cities, including predicting maintenance needs, enabling easy editing of environmental entities, calculating open space profiles, visualizing historical sensor data, predicting water accumulation on roads, simulating vegetation growth, checking collisions between existing and proposed features, integrating citizen reports, providing advice on renovation projects, linking documents to objects in the model, predicting garbage collection frequency, predicting parking occupancy, visualizing renovations or new projects, and predicting or recommending maintenance activities based on historical data.

Digital Twins for Cities addresses these needs by providing a comprehensive platform that integrates real-time data, historical records, simulation capabilities, and visualization tools. By leveraging these capabilities, stakeholders can make informed decisions, optimize resource allocation, improve maintenance planning, enhance urban design, and create sustainable and livable urban environments.

The use of Digital Twins in the pilot area of Molenakker of the municipality of Weert serves as a valuable testbed for refining the technology and establishing best practices. Lessons learned from this implementation can be applied to similar urban areas, facilitating wider adoption and implementation of Digital Twins in cities throughout the Netherlands and beyond.

The interviews conducted with various managers responsible for the management of environmental units in the municipality of Weert have been instrumental in providing answers to key questions regarding the implementation of Digital Twins. These interviews have shed light on the current methods used to manage environmental units in the public space, the expectations and desires of municipalities regarding Digital Twins, and how a Digital Twin can be effectively used in the management of environmental units. In addition, the findings from these interviews have highlighted the numerous benefits of using Digital Twins over current management methods, including improved decision making, optimized resource allocation, enhanced maintenance planning, and the creation of sustainable and livable urban environments. The valuable information gathered through these interviews has provided a solid foundation for the exploration of Digital Twins in Weert and has paved the way for refining the technology and establishing best practices. The lessons learned from this pilot implementation in the Molenakker neighborhood can be applied to similar urban areas, facilitating wider adoption and implementation of Digital Twins in cities throughout the Netherlands and beyond. The remaining questions are answered using information derived from practical insights in the following chapters.

4 DEVELOPMENT PROCESS OF THE DIGITAL TWIN

The construction of a Digital Twin for managing the environmental entities in the public space involves several steps. These steps are derived from the requirements gathered from the literature and interviews discussed in Chapter 2 and 3 respectively. A Digital Twin for cities must integrate physical assets, virtual models, and real-time data. It should offer different levels of sophistication, from basic virtual prototypes to advanced intelligent systems. This integration requires the incorporation of multiple data sources, including sensors and data from environmental entities in the public space. The Digital Twin should effectively use sensor data for real-time monitoring, analysis, and decision making. Ensuring accurate and up-to-date data is critical for reliable insights and decision support. Continuously updating models and incorporating real-time data is necessary to maintain relevance. Specific requirements such as maintenance forecasting, historical data visualization, and citizen integration should be addressed. A comprehensive platform is needed that provides real-time data integration, simulation capabilities, and visualization tools. In addition, lessons learned from pilot implementations can be used to refine the technology and establish best practices for wider adoption and implementation in cities.

According to several studies and examples (Boje et al., 2020; Fei et al., 2019; Schrotter & Hürzeler, 2020; Sepasgozar, 2021), the process can be divided into six main stages: data collection, data processing, model creation, integration, updating, and visualization. The six stages are described below and visualized in Figure 7. Each stage is discussed in more detail in the corresponding section later in this chapter.

S1 Data Collection: The first stage involves collecting data from various sources such as sensors, satellite imagery, and public databases. The data should include information about the physical characteristics of the public space, such as size, shape, and location, as well as information about how the space is used, such as pedestrian or bike.

S2 Data Processing: The data collected in the first step must be processed to ensure that it is accurate, consistent, and clean enough to be used for modeling in the third step.

S3 Model creation: The third step involves modeling the processed data from step two to create a virtual representation of the city in 3D, including buildings, infrastructure, terrain, and other features.

S4 Integration: The fourth step is to integrate the new and existing sensors into the model to provide the model with real-time data on energy consumption, traffic, water, or other desired information.

S5 Update: The fifth stage begins when the initial model is created. This stage keeps the model up-to-date by continuously updating the model as new data becomes available due to changing conditions in the public space.

S6 Visualization: The final stage is to create a dashboard that visualizes the Digital Twin and provides actionable insights. The dashboard should allow for interactive exploration of the public space and provide insight into the potential impact of different interventions.

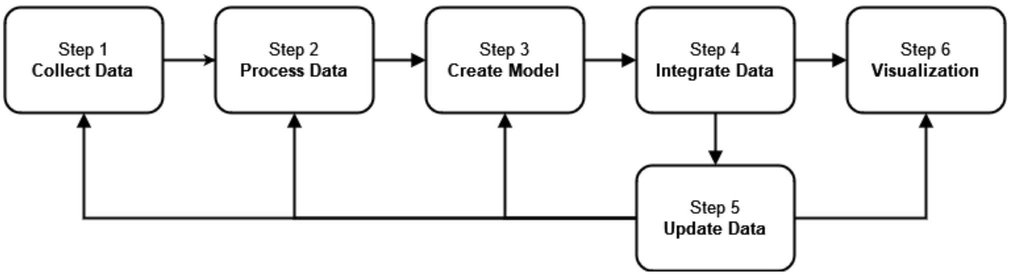

Figure 7 Development flow for Digital Twins

4.1 DATA COLLECTION

This section describes the data needed to build a Digital Twin for municipalities. It consists of both feature data and real-time sensor data. Both types of data are described below, including their possible data types. Section 6.1, provides more detailed examples related to the pilot area.

4.1.1 COLLECTION OF FEATURE DATA

The foundation of the Digital Twin is constructed using feature data, either collected from public sources or from internal databases of the municipalities themselves. A list of possible datasets that can be implemented in a Digital Twin is shown in Table 2 below. The sources for each dataset depend on the data type, so no source is shown. The sources for the pilot area on the other hand, are referenced in Section 6.1.

Table 2 Possible datasets for collection

Dataset	Preferred data type	Other possible data types
Aerial Imagery	Raster	-
Borders	File geodatabase	Shapefile or CityGML- Requires more processing
Bridges	[2D] File geodatabase [3D] Multipatch	[2D] Shapefile or CityGML – requires more processing [3D] Any other 3D data type – requires more processing
Buildings	CityJSON – LOD 2.2 (SPOTinfo – for additional info)	File geodatabase – Maximum level LOD 2 GKPG (GeoPackage) – Requires more processing OBJ (Object File) - Missing attribute data
Height map	LiDAR – better filtering	Raster or TIN surface – fewer options
Parcels	File geodatabase	Shapefile or CityGML- Requires more processing
Roads	File geodatabase	Shapefile or CityGML- Requires more processing
Sewerage	[2D] File geodatabase [3D] Multipatch	[2D] Shapefile or CityGML – requires more processing [3D] Any other 3D data type – requires more processing
Street Furniture	[2D] File geodatabase [3D] Multipatch	[2D] Shapefile or CityGML – requires more processing [3D] Any other 3D data type – requires more processing
Surface water	File geodatabase	Shapefile or CityGML- Requires more processing
Technical Installations	[2D] File geodatabase [3D] Multipatch	[2D] Shapefile or CityGML – requires more processing [3D] Any other 3D data type – requires more processing
Utility cables	File geodatabase	Shapefile or CityGML- Requires more processing
Vegetation	File geodatabase	Shapefile or CityGML- Requires more processing

4.2 DATA PROCESSING

To effectively utilize the collected data and facilitate the creation of a Digital Twin, a basic data processing stage is essential. This stage includes a range of operations, from simple attribute adjustments to complex feature modifications and analysis using geoprocessing tools. The order in which the data is processed is critical, as certain processed data may be essential for processing subsequent datasets. While ArcGIS Pro is a widely used geoprocessing tool, there are alternative GIS processing tools with comparable functionality. This discussion will examine each step of the data processing process, accompanied by a tabular presentation of the corresponding geoprocessing tools, their functions, input requirements, and resulting output. It should be noted that the processing time of each geoprocessing tool depends on the size and complexity of the datasets under consideration. Larger datasets may require longer processing times than smaller datasets. In addition, the availability and efficiency of hardware resources, including processing power and memory, can also affect the overall processing time.

4.2.1 AREA OF INTEREST

The first step in processing the data is to determine and create a polygon that represents the outer boundary of the Digital Twin, called the area of interest. This polygon will later be used for clipping other feature data. This polygon can be derived using the collected boundary data, which contains feature data on municipality boundaries or neighborhoods as polygons. Multiple municipalities or neighborhoods can be joined to create a single outer boundary polygon. It is also possible to manually create a polygon using a new layer. Table 3 shows the process of creating an Area of Interest including the input and output.

Table 3 Processing Area of Interest

Input	Polygons, boundaries in GIS format, or new polygon layer	
Tools	Export Features	Exports features based on manual selection or filter expression
	Dissolve	Dissolves multiple features in a single feature
Output	Polygon representing the Area of Interest	

4.2.2 AERIAL IMAGERY

The second step in data processing is to merge and clip the collected aerial imagery and export it to the desired resolution. Higher resolution will provide more detail, but will drastically increase processing and loading times later in the process. Table 4 shows the process of creating the Aerial Imagery including the input and output.

Table 4 Processing Aerial Imagery

Input	Aerial Image in Raster format	
Tools	Clip Raster	Clips selected Raster to a selected extent
	Export Raster	Exports selected Raster to desired format and resolution
Output	Raster of Aerial Imagery clipped to Area of Interest	

4.2.3 LIDAR

The third data to be processed is the LiDAR dataset, as this will be used to create the terrain surface. The LiDAR dataset needs to be converted or already be in .LAS (uncompressed) format instead of .LAZ (compressed) so that it can be classified using the geoprocessing tools in ArcGIS.

First, to limit the size of the LiDAR, it is best to trim the .LAS file to the output of 4.2.1. This will drastically reduce the processing time for upcoming geoprocessing. Optionally, the LAS dataset can be colorized using the aerial imagery from 4.2.2. Additionally, the LAS data may require additional classification. This can be done using several geoprocessing tools or manually using the LiDAR editing toolbar. See Table 5 for the geoprocessing tools used, including the input and output generated.

Table 5 Processing LiDAR Data

Input	LiDAR Data in .LAS or .LAZ format	
Tools	Convert LAS	Converts .LAZ to .LAS format or vice versa
	Extract LAS	Trims .LAS to a selected extent
	Colorize LAS	Applies RGB colors from aerial imagery to LAS points
	Classify LAS Buildings	Classifies building rooftops and sides in LAS data
	Classify LAS by Height	Classifies LAS points based on their height from the ground surface
	Classify LAS Ground	Classifies ground points from LAS data
	Classify LAS Noise	Classifies LAS points with anomalous spatial characteristics as noise
	Classify Tree Points using Deep Learning	Classifies vegetation points from LAS data using deep learning
Output	LiDAR dataset in .LAS format with correct classification	

4.2.4 DTM – DIGITAL TERRAIN MODEL

The digital terrain model is created by overlaying the ground surface raster with the water surface raster using a raster geoprocessing tool. The creation of both raster surfaces is described below.

GROUND SURFACE

After the LiDAR dataset is created, the ground surface can be created from the ground points and then be interpolated to create a smoother surface. There are several interpolation options, but Bekele et al. (2003) conclude that kriging (an interpolation method based on the Guassian process governed by prior covariances (Chung et al., 2019)) performs better than IDW (inverse distance weighted interpolation, which explicitly assumes that things that are close to each other are more similar than those that are farther apart (Esri, n.d.)). Gotway et al. (1996) found that kriging outperformed IDW and was more stable. ArcGIS Pro provides an improved kriging method called Empirical Bayesian Kriging (EBK). This requires the LiDAR data to be converted to Multipoint, after which it can be used as input for EBK. EBK requires the user to specify an output cell size. This cell size determines the detail of the terrain surface; smaller cell sizes dramatically increase processing time.

To further increase the level of detail and better separate elevation levels, EBK can be performed using smaller feature pieces such as road types. For example, if you separate the interpolation of a road and a sidewalk, the curb will be more visible because the individual EBKs will not smooth out the transition of the adjacent features as much as a single feature EBK would. Keep in mind that this requires even more processing power, and therefore time and resources.

WATER SURFACE

The water surface is created using the same method, but in most cases there are not many water points in the LiDAR data because water tends to absorb almost all of the lasers used to collect the LiDAR data (Team, 2022). This is not a major problem since water features should have the same water level across most of their surface due to gravity. Therefore, EBK will expand and smooth out the surface beyond the known water points. This surface is then clipped using water surface polygons collected during the data collection phase. Table 6 shows this process including input and output.

Table 6 Processing Digital Terrain Model

Input	LiDAR Data with ground & water points	
Tools	LAS to Multipoint	Converts LAS points to Multipoints
	Empirical Bayesian Kriging	Interpolates and creates raster surface from Multipoints
	Clip Raster	Clips selected Raster to selected extent
	Mosaic To New Raster	Combines multiple Rasters based on user defined priority
Output	Digital Terrain Model in Raster format	

4.2.5 BUILDINGS

3D building blocks can be collected from public datasets such as 3D Bag, but some data processing is required to convert them to Multipatch objects. Multipatch is a data format used by the ArcGIS suite to visualize 3D objects. The 3D Bag can be downloaded in different levels of detail, namely 1.2, 1.3, and 2.2. Figure 8 shows a representation of these levels of detail. Higher LOD means more data, so for large cities this may be a consideration. The 3D bag is created from 2D polygons extruded using elevation data from AHN3 (AHN, 2020d).

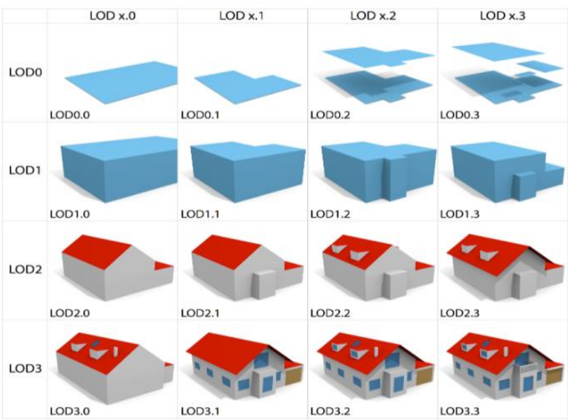

Figure 8 LOD specification for 3D building models (Biljecki et al., 2016)

Esri Nederland Content (2022) describes that to convert the CityJSON dataset from the 3D Bag to Multipatch in ArcGIS Pro, the Data Interoperability Extension is required. This extension uses the FME framework to convert the dataset into the correct file format for use in ArcGIS. In addition, more detailed buildings created in SketchUp or similar software can be imported as a Multipatch. For example, if a landmark is often used for geolocating. Table 7 shows this process, including input and output.

Table 7 Processing Buildings

Input	3D Building data	
Tools	Data Interoperability Extension	Converts CityJSON to Multipatch
	Import 3D Files	Imports one or more 3D models into a Multipatch feature class
Output	3D Buildings block in Multipatch format	

4.2.6 BRIDGES

Bridges can be imported either as 2D polygons or as fully detailed 3D models. Importing these 3D models requires a single process to convert the 3D model into a Multipatch. This 3D model can be created using modeling tools such as SketchUp or similar. 2D polygons, on the other hand, require more manual processing to create 3D Multipatches.

The first step is to determine if the LiDAR dataset contains bridge points. If not, this must be done manually. For best results, it is best to define bridge deck points in a different classification than other bridge points. Make sure that the 2D polygons are in a layer that has Z values enabled so that they can be added later using geoprocessing. This Z information is derived from either a raster or triangular irregular network (TIN) surface. This surface is created from the LiDAR points classified as bridge deck using the same method as the surfaces from 4.2.4. The 3D polygon is then extruded to a certain bridge deck thickness, which should be defined as an attribute in the corresponding table. This 3D object should be converted to a Multipatch for better compatibility later in the process.

Table 8 Processing Bridges

Input	2D Features or 3D Models	
Tools	Import 3D Files	Imports 3D models into a Multipatch feature class
	LAS to Multipoint	Converts LAS points to Multipoints
	Empirical Bayesian Kriging	Interpolates and creates raster surface from Multipoints
	Update Feature Z	Updates the z-coordinates of 3D feature vertices using a surface
	Extrusion	Extrudes 3D polygons to a certain height
	Layer 3D To Feature Class	Exports feature layers with 3D display properties Multipatch features.
	Import 3D Files	Imports 3D models into a Multipatch feature class
Output	3D Bridges in Multipatch format	

4.2.7 SEWERAGE

The sewer data consists of 3 parts, the manholes, the main pipes and the connecting pipes.

The manholes are created using 2D points that are converted to 3D points using geoprocessing with DTM extraction. These 3D points are then transformed into 3D objects using a rule set that uses attributes to define the dimensions of the 3D object. This 3D object is later converted to a Multipatch using geoprocessing.

The main pipes should be a 3D line with Z-enabled vertices. In most cases, this existing Z is the invert. However, to model correctly, this Z should express the center of the pipe. Therefore, the radius is added to this Z value. This line is then converted to a 3D Multipatch using geoprocessing.

The connecting pipes can be 2D lines or 3D lines, in the case of 2D, the lines are given a certain Z height using attributes. This line is then geoprocessed into a 3D Multipatch. Table 9 shows the process of these parts.

Table 9 Processing Sewerage

Input	2D Points and Lines with corresponding attributes	
Tools	Update Feature Z	Updates the z-coordinates of 3D feature vertices using a surface
	Buffer 3D	Creates a 3-dimensional buffer around lines to produce spherical or cylindrical Multipatch features.
	Layer 3D To Feature Class	Exports feature layers with 3D display properties Multipatch features.
Output	3D sewerage system in Multipatch format	

4.2.8 UTILITY CABLES

Utility data consists mostly of polylines. These can be collected in both 2D and 3D using a KLIC report (Kadaster, 2023c). Net4s has developed a tool to import the KLIC files directly into ArcGIS (NET4s, n.d.) In the case of 2D data collection. A local standardized cross profile is used to determine the height of the different cable types. Figure 9 shows an example of such a cross profile for the municipality of Weert.

When this height data is added to the 2D lines, the resulting 3D lines are similar to the collected 3D lines. The final step is to buffer these lines into a 3D pipeline using geoprocessing. Table 10 shows the process.

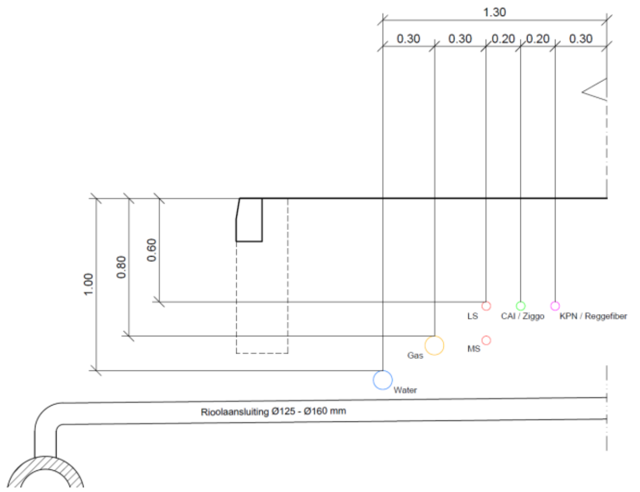

Figure 9 Cross section of cable and pipeline strip | Source: Municipality of Weert

Table 10 Processing Utility Cables

Input	2D Points and Lines with corresponding attributes	
Tools	Update Feature Z	Updates the z-coordinates of 3D feature vertices using a surface
	Buffer 3D	Creates a 3-dimensional buffer around lines to produce spherical or cylindrical Multipatch features.
	Layer 3D To Feature Class	Exports feature layers with 3D display properties Multipatch features.
Output	3D Utility Cables in Multipatch format	

4.2.9 TREES

3D trees can be created in two ways. The first one is by simply using 2D point data that is given a 3D symbology based on tree type. The starting height (ground level) of these trees is automatically derived from the DTM. The second option is to use a geoprocessing tool that derives trees from LiDAR data. This tool is shown in Table 11.

Table 11 Processing Trees

Input	2D or 3D points	
Tools	Update Feature Z	Updates the z-coordinates of 3D feature vertices using a surface
	Extract tree points using cluster analysis	Extracts 3D tree points from the lidar using cluster analysis
Output	3D trees as 2D points	

4.2.10 STREETLIGHTS

Streetlights are created in the same way as the method described in the section above. The 2D points are given a 3D symbology based on the type of streetlight. If required, a representing model of the streetlights used in the public space can be imported as symbology. Table 12 shows the single tool that is used.

Table 12 Processing Streetlights

Input	2D or 3D points	
Tools	Update Feature Z	Updates the z-coordinates of 3D feature vertices using a surface
Output	3D streetlights as 2D points	

4.2.11 GREENSPACES, ROADS & WATER AREAS

The 2D polygons collected that represent the greenspaces, roads and water areas require limited processing. The only processing required is clipping and filtering based on user input. Table 13 shows the tools that can be used for processing the polygons.

Table 13 Processing Greenspaces, Roads & Water Areas

Input	Shapefiles representing greenspaces, roads & water areas	
Tools	Export Features	Export features based on manual selection or Filter Expression
	Pairwise Clip	Clips features to a selected extent
Output	Polygon representing the greenspaces, roads & water areas	

4.2.12 MUTATING FIELDS & ATTRIBUTES

Feature layers most of the time, hold additional information about the individual features using a so-called attribute table. Sometimes it is required to change the naming of the fields or to calculate additional attributes by using other fields.

This is not done using geoprocessing but using built-in functions of the attributes tables, this is true for both ArcGIS Pro and QGIS. In addition, this can also be done using spreadsheet programs like Excel and Google Sheets, however, this requires the feature layer to be exported as a CSV. See Table 14 for the two most important tools.

Table 14 Processing Fields & Attributes

Input	Feature layer	
Tools	Calculate	Change field values by specifying a calculation expression
	Fields	Change field names, data types, and default values
Output	Feature layer with correct fields & attributes	

4.2.13 EXPORT AS WEB LAYERS

The final processing step is to export all files as web layers or similar if using other modeling software, so that they can be imported into the model created in step 3 of the development process. Feature layers can be exported using a single geoprocessing tool and require no further processing. Rasters, on the other hand, require four additional steps to export as a web layer. The first is to create a tiling scheme that can translate the raster into a compatible tiling scheme. The second step is to run a tool that translates the raster using the created tiling scheme. The third step is to export it as a tile package, after which it can be shared as a web layer. See Table 15 for the required tools.

Table 15 Processing Web layers

Input	Finalized feature layers	
Tools	Share as web layer	Exports layers to ArcGIS Online portal
	Generate Tile Cache Tiling Scheme	Creates a tiling scheme file based on the information from the source dataset
	Manage Tile Cache	Creates a tile cache or updates tiles in an existing tile cache
	Export Tile Cache	Exports tiles from an existing tile cache to a new tile cache or a tile package
	Share Package	Shares a package by uploading it to ArcGIS Online
Output	Web layers for use in ArcGIS Online	

4.2.14 CONCLUSION

In conclusion, this section provides an overview of the data processing steps required to build a Digital Twin for municipalities. The data processing stage is essential to effectively use the collected data and create the Digital Twin. This stage includes various operations ranging from simple attribute adjustments to complex feature modifications and analysis using geoprocessing tools. The order of data processing is critical, as some of the processed data may be needed to process subsequent datasets.

The data processing phase of building a community Digital Twin involves several essential actions. It begins with defining the area of interest, followed by processing aerial imagery and LiDAR data to create a terrain surface. This includes merging and clipping aerial imagery and performing various operations on LiDAR data.

To incorporate physical structures such as buildings and bridges into the Digital Twin, 3D models are collected and converted. Sewer systems are represented by creating 3D objects for manholes, main pipes, and connecting pipes. Utilities, including pipelines, are imported and converted to 3D representations.

Vegetation and natural features, such as trees and water bodies, are incorporated by representing them in 3D using point data or LiDAR information. Street lights are created by assigning 3D symbology to point locations, and additional models can be imported to enhance their representation.

Green spaces, roads, and water features are manipulated by applying basic operations such as clipping and filtering. Attribute and field manipulation is performed to modify and enhance the data, including renaming fields, calculating additional attributes, and making other adjustments.

Finally, the processed data and models are exported in appropriate formats for integration into the Digital Twin model. This allows for a comprehensive representation of the physical environment, encompassing multiple data types and utilizing geoprocessing tools.

These generalized actions provide a high-level overview of the data processing steps involved in building a Digital Twin for municipalities, ensuring the effective use of collected data to create an accurate and detailed representation of the urban environment.

Overall, the data collection and processing steps described in this section provide a foundation for building a community Digital Twin, incorporating different types of data, and using geoprocessing tools to create a detailed and comprehensive representation of the physical environment.

4.3 MODEL CREATION

Stage 3 of developing a Digital Twin for a municipality is to create a model that incorporates all the data processed in the previous stages of the development process and is able to visualize this data with sufficient quality and fluidity. Since ArcGIS is used for processing, the best solution for creating a model is to use ArcGIS Online. ArcGIS Online, as its name suggests, is an online tool that can be used from anywhere, at any time, on any device that supports a standard Internet browser and is licensed for using it. ESRI (n.d.-a) describes the tool as follows: "ArcGIS Online is a cloud-based mapping and analysis solution. Use it to create maps, analyze data, and share and collaborate. Get access to workflow-specific applications, maps and data from around the world, and tools to be mobile in the field".

4.3.1 CREATING SCENE

The first step of stage 3 is to create a Scene in ArcGIS Online. This scene can be referred to as the Digital Twin model since all data will be imported into this model in a later step. When creating a scene, the creator can choose between a Local or Global scene. Global and local scenes are different ways to visualize 3D data. Global scenes show data that spans the globe and are useful for displaying data in a global context. Local scenes are used to view data to a smaller extent and are useful for editing, analyzing, or measuring local datasets. Local scenes support geographic, projected, and custom coordinate systems, while global scenes only support WGS 84 and CGCS 2000 geographic coordinate systems (ESRI, n.d.-c). In the Netherlands, the RD coordinate system is used and since this Digital Twin is based on a local, city level, a Local scene works best.

4.3.2 IMPORTING DATA

To get the data from ArcGIS Pro to ArcGIS Online, the data needs to be converted to so-called web layers, fortunately this has already been done in the final processing step described in Section 4.2.13. Web layers are layers designed to be used in ArcGIS Online to achieve better performance & quality (ESRI, n.d.-b).

4.3.3 SYMBOLOGY

Layers can be symbolized with colors, textures, or 3D symbology to distinguish them from each other. Certain 3D layers can also be made transparent so they don't block other layers. This can also be changed on the fly. Figure 10 shows the result of a model created in ArcGIS Online with the appropriate symbology applied.

Figure 10 Model in ArcGIS Online

4.4 INTEGRATION OF REAL TIME DATA

The data previously collected and processed is based on passive, non-dynamic data. However, municipalities are also collecting data using sensors. This data is collected in real time and requires different collection and processing methods.

4.4.1 COLLECTION OF REAL TIME DATA

Data obtained from sensors must be collected in real time using Application Programming Interfaces (APIs) or other cloud solutions, while feature data can be collected using Web Feature Service (WFS). A list of possible data that can be derived in real time is shown in Table 16 below.

Table 16 Possible sensor data for collection

Team	Type of data	Collection Type
Parking	Occupancy of parking garages	API
Green & Waste	Temperature	API
	Humidity	API
	Fill levels of containers	API
	Externally hosted green & waste feature data	WFS
Road Infrastructure	Traffic count	API
	Noise	API
	Air quality	API
	Externally hosted road feature data	WFS
Technical Installations	Traffic light status	API
	Lighting status	API
	Externally hosted lighting feature data	WFS
Water & Sewerage	Pump status	API
	Throughput	API
	Water levels	API
	Externally hosted sewerage feature data	WFS

**Real time data is not publicly available, so no references mentioned.*

4.4.2 INTEGRATION IN ARCGIS

ArcGIS allows users to integrate real-time data into their own applications using either WFS or API. This integration capability provides many benefits to users, including enhanced compatibility, streamlined workflows, and improved data interoperability. By integrating real-time data into their applications, users can access and analyze the most up-to-date information about various city systems and assets. Whether it's real-time traffic data, weather updates, sensor readings, or social media feeds, ArcGIS allows users to seamlessly integrate this dynamic information into their spatial applications. This ensures that decision-making processes are based on the latest data, enabling timely responses and improved situational awareness (Esri, n.d.-m).

WFS INTEGRATION

To use WFS integration in ArcGIS, a new server connection must be created using the "Add WFS Server" option in ArcGIS Pro. This will open a new screen where you can enter the server URL, as well as the username and password if required for the connection. Once the WFS connection is established, real time layers can be added to the model using the catalog menu, showing the layer names.

API INTEGRATION

API integration requires a connection to the ArcGIS GeoEvent Server. This online application allows users to graphically model the required input and output of specific feature data in combination with sensor data collected via APIs. It is possible to process the collected API in real time using numerous calculations to achieve the desired result. The result created in GeoEvent Server can later be added to the model in ArcGIS Pro or Online using a real-time connection.

4.5 UPDATE DATA

To keep the Digital Twin imperative, the data needs to be as up-to-date as possible. The most efficient way of doing this is to manage the data from the Digital Twin. When adjustments are made in the physical space, edits need to be executed in the Digital Twin.

It is important for municipalities that the data is not only for visualization but can also be used to manage the public space. Therefore, it is required that assets in the Digital Twin can be modified on the fly and real-time data is visible directly from the model.

This requirement is another reason why ArcGIS Online is used for running the model. Whenever adjustments are made in ArcGIS Online, these adjustments are synced with the server in real-time, so that all users have access to up-to-date data.

ADDING NEW DATA
When new data is collected, stages 2 up until 4 can be repeated in ArcGIS Pro if necessary, without changing the initial data. However, if a dataset with similar properties is collected, it can be appended from within ArcGIS Online.

EDITING DATA
ArcGIS Online provides users with easy access to editing existing data, this can vary between editing the attributes of a feature, editing its geometry/location or adding/removing features all together. Figure 10 shows the editing tool on a feature in ArcGIS Online.

EDIT TRACKING
To keep track of edits, ArcGIS Online has a built-in tracker that is appended to each layer's attribute table. This attribute shows when the last edit was made and by whom.

Figure 11 Editing tool in ArcGIS Online

4.6 VISUALIZATION

To quickly view the data associated with the features of the Digital Twin model, a dashboard of the desired information is required. ArcGIS Online provides the ability to create this dashboard manually. Based on the feature layers implemented in the model as of 4.3, it can be used to create charts, graphs, specific maps, or lists. All of these elements can be placed on a single dashboard, giving the user the ability to get all the information they need at a glance. The information displayed on this dashboard is updated whenever adjustments are made to the Digital Twin model. Of course, the Digital Twin itself can also be used to gather information, but it does not provide the ability to view the generated diagrams in the 3D environment. A dashboard example is created for the pilot area in section 6.6.

4.7 CONCLUSION

In conclusion, the construction of a Digital Twin for managing the environmental entities of the public space involves several steps, as supported by studies and examples. The process can be divided into six main stages: data collection, data processing, model creation, integration, updating, and visualization.

The first stage, data collection, involves gathering information from various sources such as sensors, satellite imagery, and public databases. This data should include physical characteristics of the public space and information about its use.

The second stage, data processing, focuses on ensuring that the collected data is accurate, consistent, and suitable for modeling. This step may include cleaning and refining the data.

In the third stage, model creation, the processed data is used to develop a virtual representation of the public space in 3D. This model includes buildings, infrastructure, terrain, and other relevant features.

The fourth stage, integration, involves incorporating new and existing sensors into the model. This allows the Digital Twin to receive real-time data on energy consumption, traffic, water, or other desired information.

The fifth stage, updating, ensures that the Digital Twin remains up-to-date by continuously updating the model with new data. This is necessary to reflect any changes in the conditions of the public space.

The final stage, visualization, focuses on creating a dashboard or interface that allows users to interact with the Digital Twin. This visualization should provide actionable insights and allow for exploration of the public space, as well as show the potential impact of different interventions.

In the context of data collection, both feature data (passive) and real-time sensor data are important. Feature data, collected from public sources or internal databases, forms the basis of the Digital Twin. Possible datasets for feature data collection include aerial imagery, building data, road data, vegetation data, and more.

Real-time sensor data, on the other hand, is obtained using sensors and collected in real time through APIs or cloud solutions. Examples of sensor data that can be collected include parking occupancy, temperature, humidity, particulate matter, traffic counts, noise levels, and various utility statuses.

Overall, the process of creating a Digital Twin for public space management requires careful data collection, processing, model creation, sensor integration, regular updates, and effective visualization. These steps work together to create a powerful tool that can assist in the management and planning of public spaces.

5 SYSTEM ARCHITECTURE FOR IMPLEMENTATION

Implementing a Digital Twin in a municipality requires a robust and well-designed system architecture to effectively manage and utilize the vast amount of data involved. Using the ArcGIS suite as the base platform makes implementation easier.

First, a summary of the requirements is described, and then the software used is elaborated in combination with an example structure for the implementation of a system architecture.

5.1 REQUIREMENTS

Below are some key components and considerations for the system architecture required for municipal Digital Twins (Chevallier et al., 2020; Y. Wang et al., 2023):

Data collection and integration: Digital Twins rely on data from multiple sources, including sensors, IoT devices, public records, and other relevant databases. The system architecture must facilitate the collection, integration, and normalization of this diverse data into a consistent format that can be used to build and update the Digital Twin.

Cloud infrastructure: Given the vast amounts of data involved in Digital Twins, a cloud-based infrastructure is often required to store, process, and analyze the data. Cloud platforms offer scalability, flexibility, and cost-effectiveness, allowing municipalities to handle large volumes of data and access computing resources as needed.

Data management and storage: The architecture should include a robust data management system that can efficiently handle both structured and unstructured data. This may include the use of databases, data lakes, or data warehouses to store and organize data in a way that enables easy retrieval and analysis.

Visualization and user interface: Digital twins are valuable tools for visualizing and understanding complex urban systems. The system architecture should incorporate visualization techniques and user interfaces that allow municipal stakeholders to effectively interact with and explore the Digital Twin. This may include 3D modeling, geospatial mapping, and real-time data visualization.

Data Analytics and AI: Advanced analytics and artificial intelligence (AI) capabilities play a critical role in extracting insights from the Digital Twin. The system architecture should support the integration of analytics tools and AI algorithms that can process the data, identify patterns, predict outcomes, and support decision-making processes.

Connectivity and communication: To ensure real-time monitoring and seamless data flow, the system architecture must address connectivity requirements. It should enable the integration of various communication protocols, such as IoT protocols, to facilitate data exchange between sensors, devices, and the Digital Twin platform.

Security and privacy: Given the sensitivity of municipal data and potential cyber threats, security and privacy considerations are paramount. The system architecture should incorporate robust security measures, including encryption, access controls, and authentication mechanisms, to protect the Digital Twin and the data it contains.

Scalability and Future Growth: A well-designed system architecture should be scalable and able to accommodate future growth. Communities evolve over time, and the Digital Twin should be able to adapt to changes and incorporate new data sources, technologies, and capabilities as needed.

5.2 SOFTWARE

For this research, the ArcGIS suite is used for several reasons. The first is the license provided by TUe. Second, the capabilities and general workflows, and finally, the professional support available to the researcher as well as to the municipalities that will be using the framework. The following sections describe each software package in more detail.

5.2.1 ARCGIS PRO

ArcGIS Pro is a robust GIS software that provides a range of advanced mapping, analysis, and data management capabilities. It is widely preferred by organizations and individuals engaged in professional GIS work. While ArcGIS Pro stands out among other GIS software options, it's worth considering the benefits of alternative programs. Some notable alternatives include QGIS, GRASS GIS, and MapInfo. By evaluating different GIS software options, you can find the one that best meets your specific project requirements and user preferences. Here are some advantages of ArcGIS Pro over other GIS software:

- Many features in one software package
- 3D visualization capabilities
- Leading GIS application for professionals

Other software packages such as QGIS and MapInfo also have their advantages over ArcGIS, but these advantages are not directly related to the development of a Digital Twin. For example, QGIS is open source and has a wide range of plugin support, making its possibilities endless.

In the required system architecture of a municipality, ArcGIS Pro is used on the master client to set up the initial model, make large mutations, add new datasets, or perform large analyses. Figure 12 shows ArcGIS Pro and its user interface.

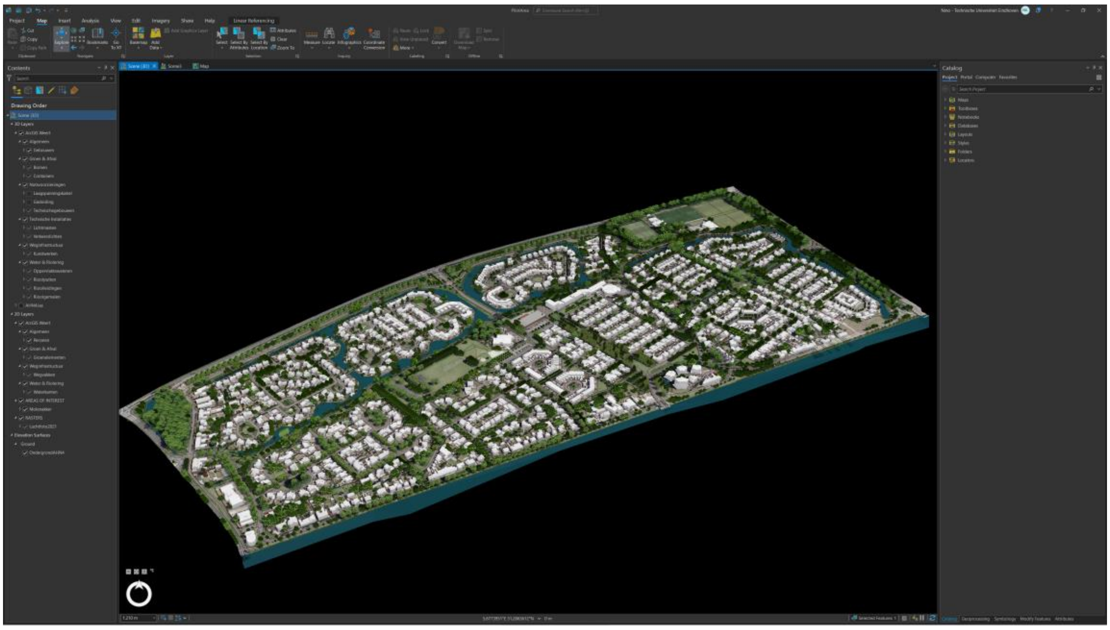

Figure 12 Digital Twin in ArcGIS Pro in 3D viewer

To extend the capabilities of ArcGIS Pro, some first-party extensions are used, such as:

- ArcGIS Pro Data Interoperability Extension, for importing other formats such as CityJSON.
  (The ArcGIS Data Interoperability extension for Desktop is a comprehensive toolset that operates within the geoprocessing framework using Safe Software's FME technology. This integrated spatial extract, transform, and load (ETL) solution enables seamless data integration and manipulation (Esri, n.d.-b)).
- ArcGIS Pro Deep Learning Libraries, for running deep learning algorithms.
  (The Deep Learning Libraries extension provides libraries to run powerful Deep Learning analysis tools that enable the identification of connections in data that may be overlooked by the human eye (Esri, n.d.-g)).

5.2.2 ARCGIS ONLINE

ArcGIS Online is an extension to the ArcGIS Pro application that runs in any browser because it is hosted in a cloud or server, making it accessible from any device with a simple http(s) link. Because ArcGIS Online runs online, it requires almost no computing power from the device it runs on. This makes it easy to use on any device with an Internet connection. ArcGIS Online allows users to manage, visualize, and edit data created in ArcGIS Pro. It includes a dedicated scene viewer (3D visualizer) with real-time editing capabilities and the ability to create applications that visualize data in multiple formats, such as 2D maps with graphs and interactive map views of the 3D model with integrated sensor readings, resulting in dashboards that present important data at a glance.

5.3 EXAMPLE STRUCTURE

To give a brief example of what such a system architecture should look like at the back end, the following diagram is created in Figure 12. The system consists of several databases containing the required data, which are connected to the various servers via the network. This network is also connected to the Internet, making it discoverable worldwide. Clients from different forms (PC, Tablet, or Phone) and locations can use this connection to connect to the servers and thus to the data needed to perform their tasks. For large mutations (new datasets, large analyses, or calculations) to the data, a master client can be used to run ArcGIS Pro locally instead of in the cloud. For smaller mutations (attribute changes), other clients can use the online portal (ArcGIS Online), which runs easily from any browser.

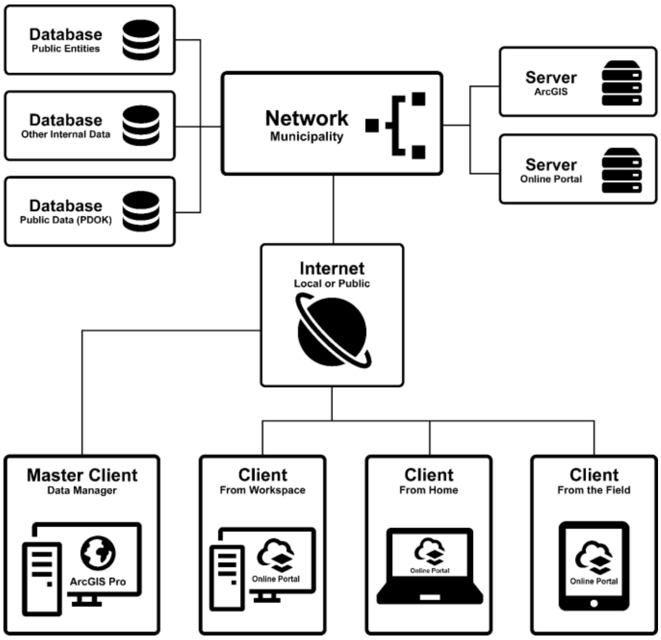

Figure 13 System architecture for municipalities using ArcGIS

5.4 CONCLUSION

Implementing a Digital Twin in a municipality requires a well-designed system architecture to effectively manage and use the data. ArcGIS software, such as ArcGIS Pro and ArcGIS Online, is used for its features and support. The system architecture must meet requirements such as data collection and integration, cloud infrastructure for storage and processing, robust data management and visualization tools, data analytics and AI integration, connectivity protocols, security measures, and scalability.

ArcGIS Pro is a powerful GIS software with features such as advanced mapping and analysis, 3D visualization, and customer support. It is used on the master client to build the initial model and perform large-scale analysis. ArcGIS Online is a browser-based extension hosted in the cloud and accessible from any device with an Internet connection. It allows users to manage, visualize, and manipulate data created in ArcGIS Pro, including a dedicated scene viewer and the ability to create data visualization applications.

A sample system architecture includes interconnected databases connected to servers and the Internet, allowing clients to access data for their tasks. Large changes can be made using the master client running ArcGIS Pro locally, while smaller attribute changes can be made using the online portal (ArcGIS Online). This architecture facilitates connectivity, scalability, and easy data retrieval.

Overall, the combination of a well-designed system architecture and ArcGIS software provides municipalities with the necessary tools to efficiently manage and use data in their Digital Twin implementations.

6 PILOT AREA MUNICIPALITY OF WEERT

To test the capabilities of the framework described in Chapter 4, it is tested on a pilot area within the municipality of Weert. The following sections show screenshots of the model in ArcGIS Pro, but for a better view of the model, Appendix III is included to describe to the reader how to view the model in ArcGIS Online, including all the layers and editing possibilities.

6.1 DATA COLLECTION

The following datasets are collected for constructing the Digital Twin of Molenakker.

Table 17 Collected data for pilot area

DATASET	DATA TYPE	SOURCE
3D BAG Basisregistratie Adressen en Gebouwen	CityJson	Tudelft3d (TU Delft 3D Geoinformation, n.d.)
AHN4 Algemeen Hoogtebestand Nederland	LiDAR	Algemeen Hoogtebestand Nederland (AHN, 2023)
BGT Basisregistratie Grootschalige Topografie	File geodatabase	Kadaster (Kadaster, 2023)
CBS Wijk- en Buurtkaart	File geodatabase	Centraal Bureau voor de Statistiek (CBS, 2023)
Civiele Kunstwerken	Shapefile	Gemeente Weert *Sourced, internally
BRK Basisregistratie Kadaster	File geodatabase	Kadaster (Kadaster, 2023b)
Groenelementen	Shapefile	Gemeente Weert *Sourced, internally
Kabels & Leidingen	XML	Kadaster (Kadaster, 2023c)
Luchtfoto	Raster	Beeldmateriaal Nederland (Beeldmateriaal Nederland, 2023)
Technische Installaties	Shapefile	Gemeente Weert *Sourced, internally
Water & Riolering	Shapefile	Gemeente Weert *Sourced, internally
Postcodevlakken	File geodatabase	Centraal Bureau voor de Statistiek
Weginfrastructuur	Shapefiles	Gemeente Weert *Sourced, internally

6.2 DATA PROCESSING

The steps described in Section 4.2 are performed for the pilot area in this section.

6.2.1 AREA OF INTEREST

The area of interest was derived from the dataset "CBS Wijk- en Buurtkaart" as it represents the border of the neighborhood "Molenakker". Figure 14 shows the Area of Interest in 3D view.

Figure 14 The Area of Interest

6.2.2 AERIAL IMAGERY

The latest aerial image from *Beeldmateriaal Nederland* is collected in Raster format using a WMTS service and clipped using the polygon representing the Area of Interest. The result of the raster is shown in Figure 15. Notice the difference in quality between the inside and outside of the Area of Interest. Since the aerial imagery inside the Area of Interest is processed, it has a higher resolution no matter the scale, while the WMTS resolution is changed based on scale to save bandwidth.

Figure 15 Aerial Imagery for Pilot Area

6.2.3 LIDAR

The LiDAR data collected from Algemeen Hoogtebestand Nederland is in compressed .LAZ format so it is first converted to .LAS after which all geoprocessing tools are run. The result is shown in Figure 16.

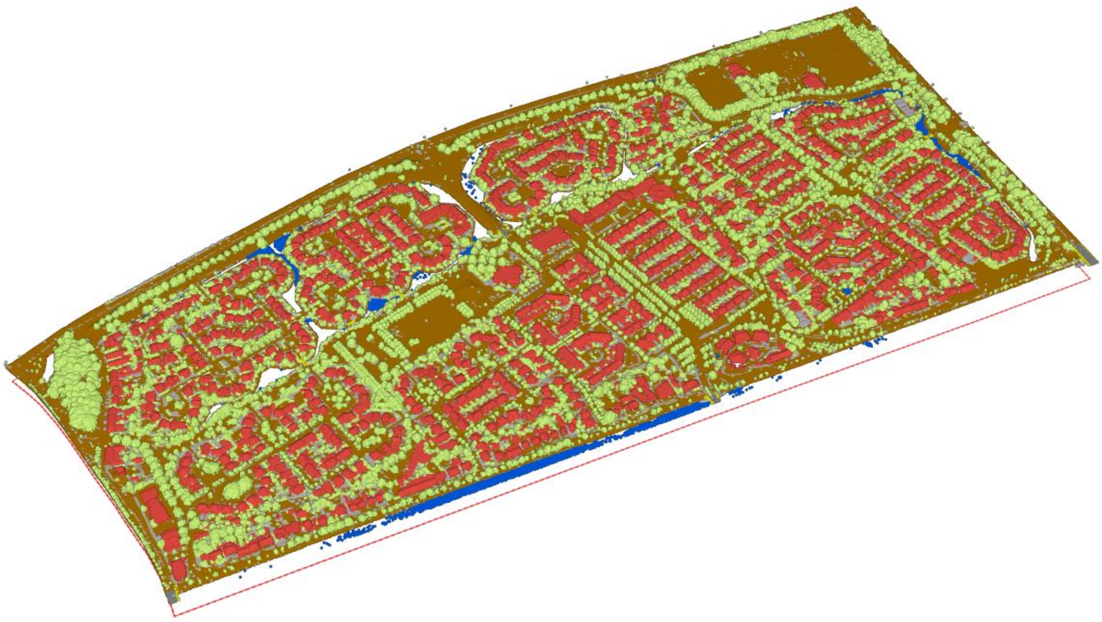

Figure 16 LIDAR Processing result for Pilot Area

6.2.4 DTM – DIGITAL TERRAIN MODEL

The DTM is created using the resulting LiDAR model described in the previous section. The result is shown in Figure 17, where the dark patches are low ground and the white patches are high ground.

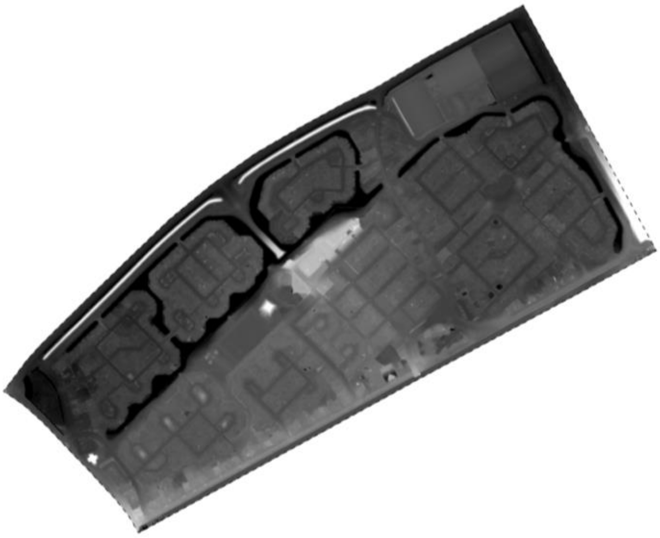

Figure 17 DTM created from LiDAR

6.2.5 BUILDINGS

The buildings are collected from the TUdelft3d in JSON format with LOD2.2 and are converted using the Data Interoperability Extension for ArcGIS Pro. Two well-known reference buildings from the pilot area are created using SketchUp and are imported to replace the blocks from the 3D BAG. The result is shown in Figure 18.

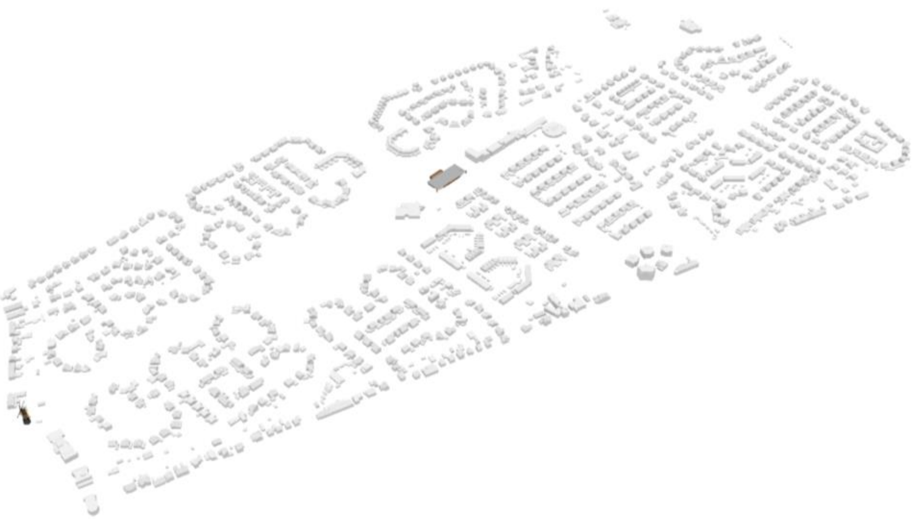

Figure 18 Processed buildings for pilot area

6.2.6 BRIDGES

The pilot area consists of a total of 6 bridges, 5 of which are identical. Therefore, the bridges are modeled in SketchUp based on technical drawings from the municipality of Weert. The result of the two bridges is shown in Figure 19.

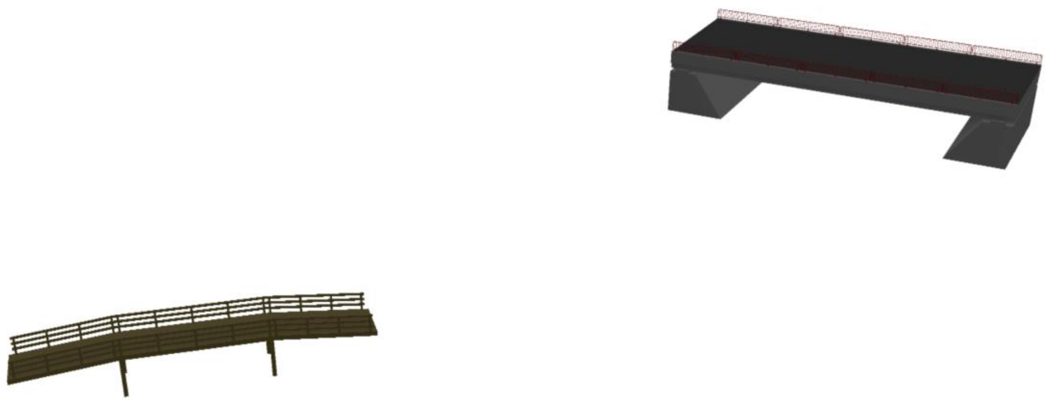

Figure 19 Bridge models for the pilot area

6.2.7 SEWERAGE

The sewerage is modeled using 2D points and lines that are collected in shapefile format. The result is shown in Figure 20.

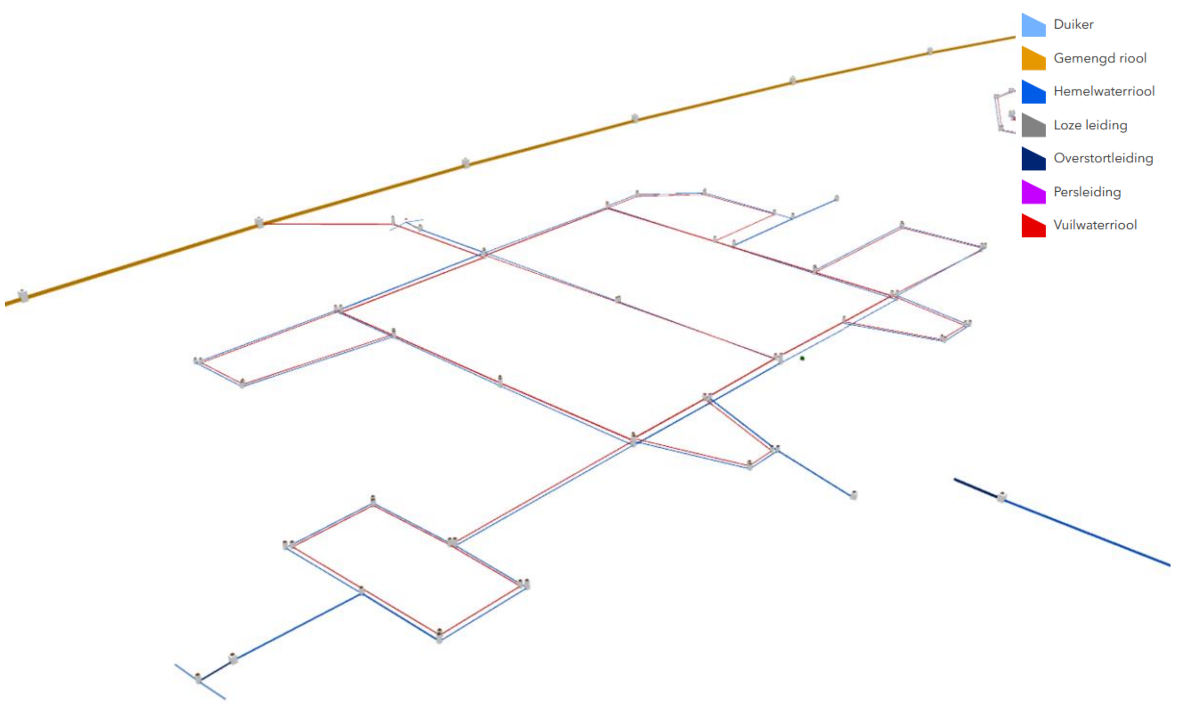

Figure 20 Part of the sewerage system for the pilot area

6.2.8 UTILITY CABLES

The utility cables consist of 2D data collected by the KLIC, which includes data from Enexis, WML, KPN and Ziggo. These companies are responsible for the supply of electricity/gas, water and data respectively. The KLIC data is imported into ArcGIS Pro using Net4s' tool, unfortunately, Net4s was only able to process one KLIC report, resulting in 3D data for half of the area of interest. Figure 21 shows the result for a part of the pilot area.

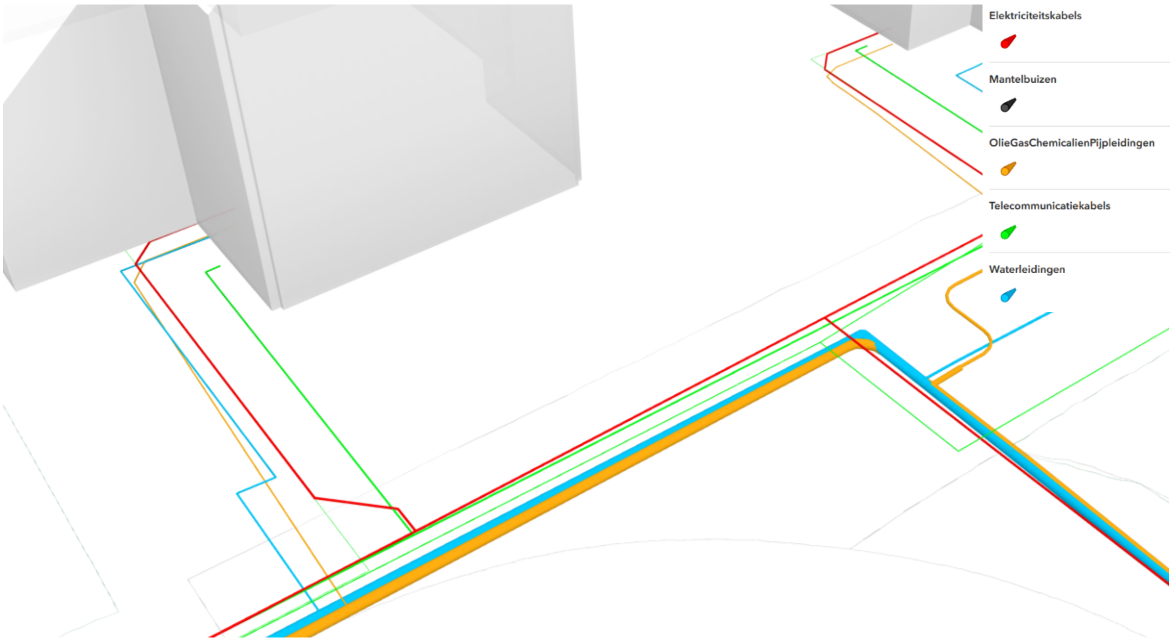

Figure 21 Utility cables for the pilot area

6.2.9 TREES

Trees are collected as 2D points for the public area, but to expand the model, trees are also created at private locations using deep learning based on LiDAR data. These points are modeled in 3D based on tree type and size. The result of the trees is shown in Figure 22.

Figure 22 Modelled trees for the pilot area

6.2.10 STREETLIGHTING

Streetlights are collected as 2D points and modeled based on type and size. Additional geoprocessing is used to rotate the 3D models to the center of the street. The result is displayed in Figure 23.

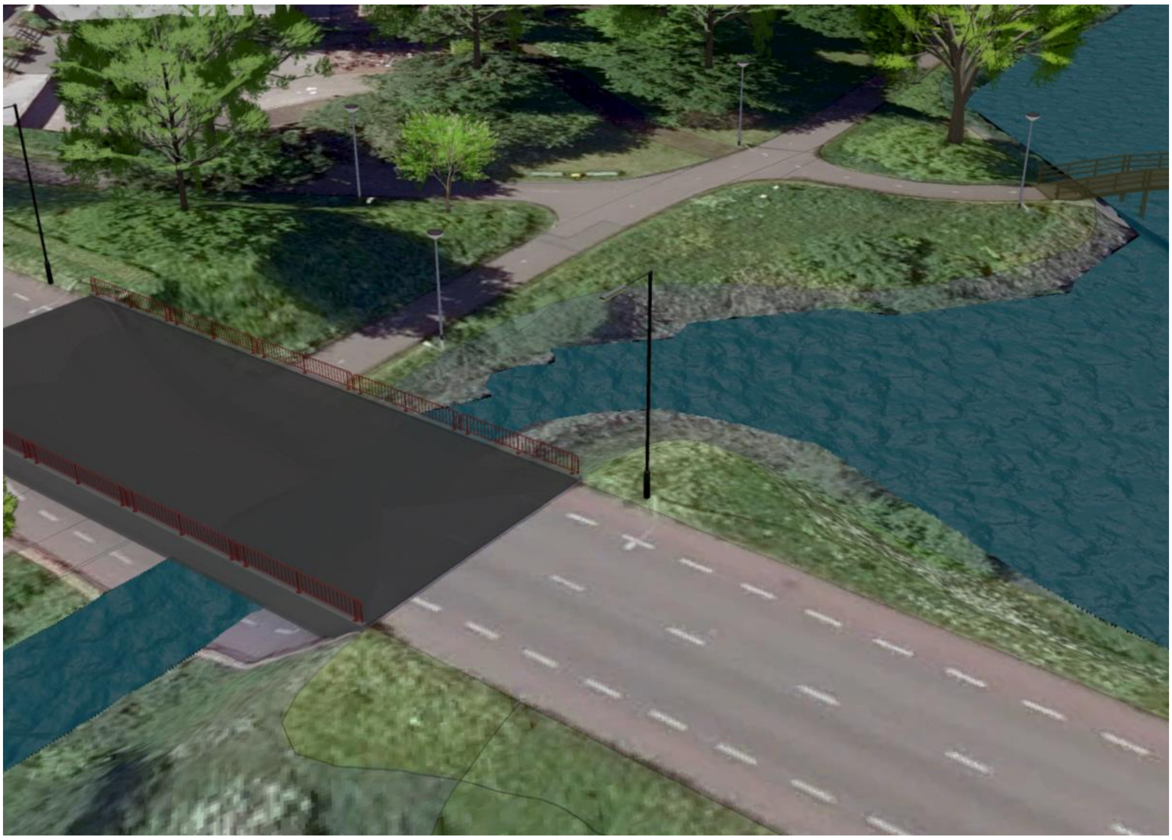

Figure 23 Streetlighting for the pilot area

6.2.11 GREENSPACES, ROADS & WATER AREAS

The polygons representing the green areas, roads, and water areas were collected internally by the municipality of Weert and only required clipping. Figure 24 shows these polygons in the 2D viewer.

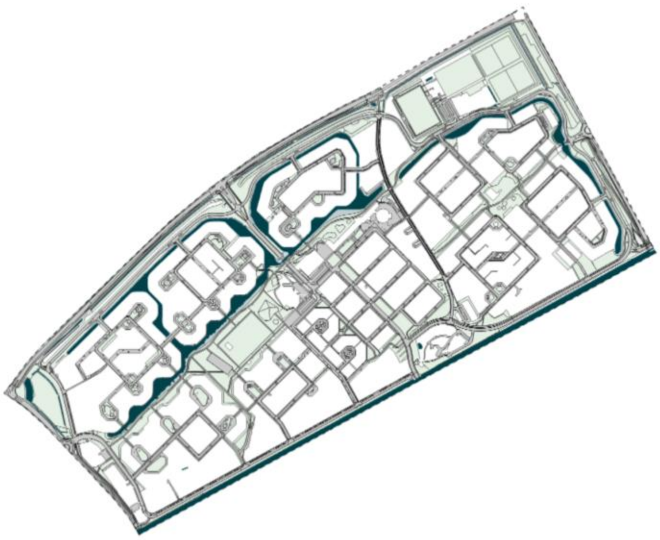

Figure 24 2D polygons representing greenspaces, roads and water areas

6.2.12 UNPROCESSED 3D LAYERS

In addition to the base layers discussed in section 4.2, a few other layers have been added that do not require any processing, besides putting them in the correct position. The layers are all imported as 3D models. These include:

- Containers for waste and glass collection (3D)
- Technical buildings (3D)
- Traffic lights (3D)
- Sewerage pumps (3D)

Containers
The containers are modeled using SketchUp and are combined with attribute data from the team Green & Waste. See Figure 25.

Technical buildings
The technical buildings are an expansion of the building blocks which are combined with attribute data from the KLIC.

Traffic lights
The traffic lights are modeled in SketchUp and provided with some additional attributes from the team *Technical Installations*. See Figure 26.

Sewerage pumps
The containers are modeled using SketchUp and are combined with attribute data from WBL (Waterschapsbedrijf Limburg).

Figure 25 Containers

Figure 26 Traffic lights

6.3 MODEL CREATION

After the layers are processed and exported to web layers, they are imported into ArcGIS Online. Each layer requires specific symbology to correctly visualize its specifications. To improve performance, the model consists of scale dependent symbology. For example, the aerial image is only displayed at a scale of less than 1:1000, above which the colored feature polygons take over. These polygons require less processing power and therefore improve performance. Figure 27 shows a screenshot of the model at a scale above 1:1000 and Figure 28 shows the model at a scale below 1:1000.

Figure 27 The "Model" in ArcGIS Online with less detail due to scale

Figure 28 The "Model" with more detail in ArcGIS Online

6.4 INTEGRATION OF SENSOR DATA

The integration of sensor data plays a critical role in the Digital Twin concept. It enables real-time monitoring, analysis and decision making, providing valuable insights into various aspects of the physical environment. Attender Green, an external manager of vegetation, provides an online dashboard and API that facilitates the collection of sensor data for integration into the Digital Twin (ConnectedGreen, n.d.).

Using the online dashboard and API provided by Attender Green, the Digital Twin can seamlessly collect data from a variety of sensors deployed throughout the city. These sensors can collect information on environmental conditions of vegetation including humidity, salt levels and temperature. The online dashboard is shown in Figure 29, visualizing the different locations of the sensors within the municipality of Weert. The different pin colors indicate the watering needs of the vegetation (Green is OK, Red means watering is required).

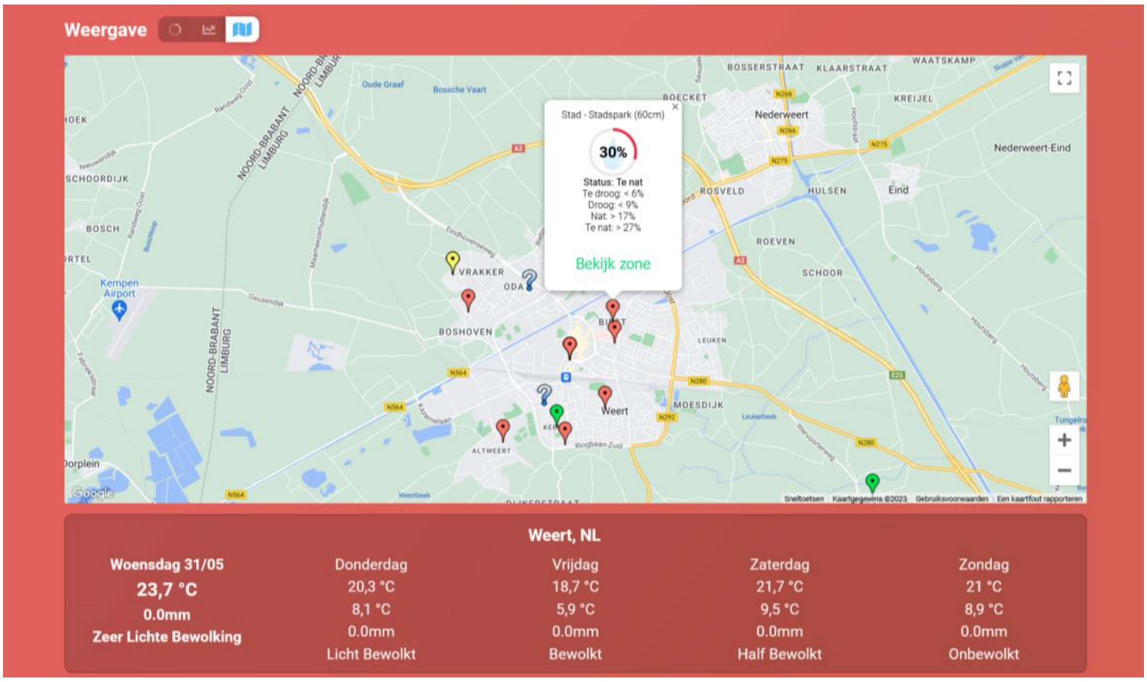

Figure 29 Screenshot of dashboard showing sensors in municipality of Weert

The collected sensor data can be transmitted to the Digital Twin in real time, allowing for immediate updates and analysis. This real-time integration empowers stakeholders with up-to-date information, allowing them to make informed decisions regarding urban planning, resource allocation, and maintenance activities. Appendix II shows the code that was used to query the JSON data into the Digital Twin.

The availability of the API further enhances the flexibility and extensibility of the Digital Twin. It allows stakeholders to access the sensor data, enabling custom data analysis, visualization, and integration with other applications or systems.

Overall, the integration of sensor data provided by Attender Green's online dashboard and API strengthens the capabilities of the Digital Twin. It facilitates the collection, analysis, and visualization of real-time sensor data, enabling cities to optimize resource utilization, improve urban planning, and create more sustainable and livable environments.

6.5 UPDATE DATA

One of the key components of the Digital Twin for managing the environmental entities of the public space is the ability to make mutations to the data in the model. These changes are applied to all locations and clients where this data is present, so that the data is always up to date. Because each client connects to an online database, this problem is addressed and handled almost instantly. The attributes showing the last editor and the time of that edit can be seen on the left side of Figure 30.

Figure 30 Editing in ArcGIS Online

As an example, a modification has been made to the selected sewer pipe type shown in Figure 30. In Figure 31, the color of the pipe has been changed, indicating a mixed system, instead of the previous red color indicating a wastewater system.

Figure 31 The result of editing

6.6 VISUALIZATION

The visualization of data in a digital twin for the management of public space environmental entities plays a critical role in providing valuable insights and facilitating effective decision making. The digital twin allows managers to visually represent various environmental parameters such as air quality, noise levels, waste management, and green spaces in an intuitive and comprehensive manner. Through interactive 2D and 3D visualizations, managers can gain a holistic view of the current state and performance of these entities.

A key feature of the Digital Twin is its flexibility, allowing managers to create personalized dashboards based on user input. Managers can customize their dashboards by selecting specific types of data, choosing appropriate charts or graphs to display the information, and even incorporating real-time sensor readings. This allows managers to focus on the most relevant information and visualize it in a way that best suits their decision-making needs.

The choice between 2D and 3D visualization depends on the specific data being analyzed and the requirements of the managers in the municipality of Weert. It may be beneficial to combine both approaches, using 2D visualizations for concise data presentation and comparisons, and 3D visualizations for exploring spatial relationships and engaging stakeholders in a more immersive way. The Digital Twin platform can integrate both types of visualizations, providing a comprehensive view of the required information for the Green & Waste team and other departments within the municipality.

By enabling managers to create customized dashboards, the Digital Twin promotes data-driven insights and empowers stakeholders to more effectively monitor and manage environmental assets. The visual representation of data enhances understanding, facilitates analysis, and supports proactive planning and resource allocation. In addition, the ability to incorporate real-time sensor data ensures that managers have up-to-date information for timely intervention and response.

As an example, Figure 32 shows a dashboard created for the team Green & Waste that includes data of all green entities as well as a chart that shows how many of the total trees have been inspected.

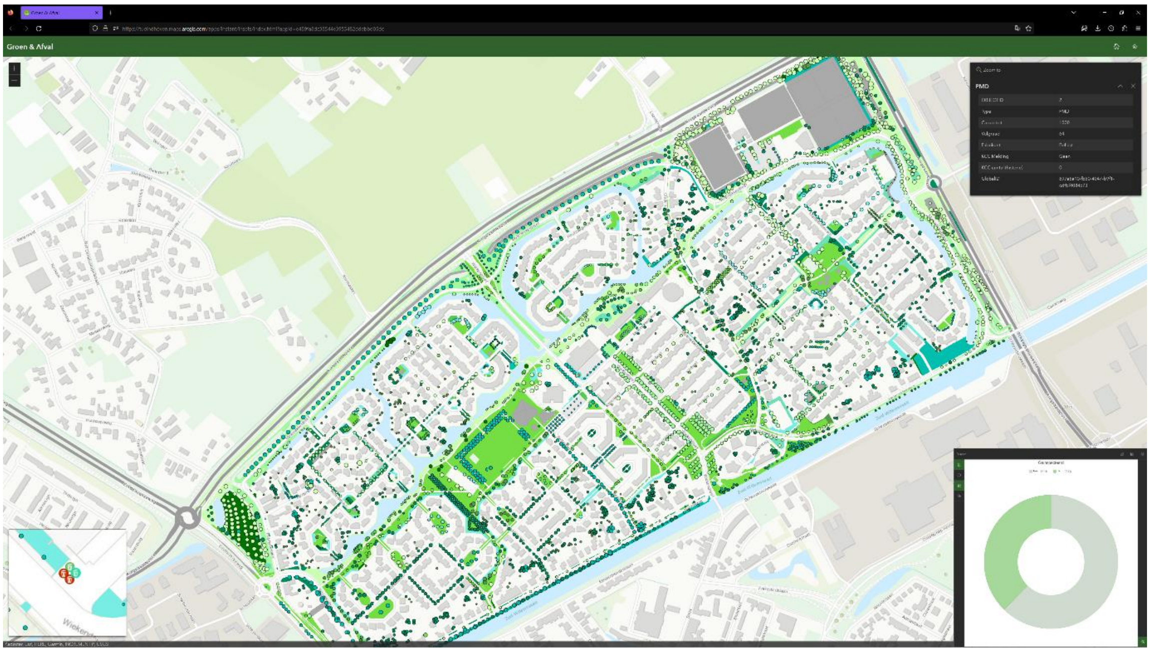

Figure 32 2D Dashboard created in ArcGIS Online based on user input

Overall, the visualization capabilities of the digital twin, coupled with the flexibility to create personalized dashboards, empower managers in their decision-making processes related to environmental entities in the public realm. This promotes efficient resource management, enhances environmental sustainability, and contributes to the overall well-being of the community.

6.7 POST-ASSESMENT

The post-assessment presentation held for the managers of the municipality of Weert went beyond a mere presentation and included an interactive session where stakeholders were interviewed afterwards to gather their perspectives on the recently created Digital Twin. The managers were asked a series of questions to express their opinions, identify areas for improvement, and discuss challenges related to the implementation and use of the Digital Twin. An overview of the questions and answers can be found in Appendix IV.

The presentation began with an overview of the creation process, highlighting the integration of insights from interviews with city managers and extensive research from relevant literature. This approach provided a strong foundation for the subsequent analysis and evaluation of the Digital Twin. Managers were presented with a comprehensive assessment of the potential benefits and functionalities of the Digital Twin. These benefits included improved decision making, enhanced collaboration, efficient resource allocation, and proactive problem identification. Concrete examples were shared to demonstrate how the Digital Twin has already facilitated informed and data-driven urban planning decisions.

Following the overview of benefits, the presentation shifted its focus to soliciting feedback and opinions from managers. A structured discussion was initiated to understand their perspectives on the practicality, effectiveness, and value of the Digital Twin in their daily operations. The managers' feedback played a critical role in identifying areas for improvement. They highlighted functionalities or features they felt were missing and suggested ways to further optimize the Digital Twin. This feedback was captured and compiled into a comprehensive list of suggested improvements, which includes:

Based on the post-assessment questions, the additional areas of improvement for the Digital Twin include:

- Attach documents (Excel, Word, or PDF) to features: The ability to attach relevant documents to specific features within the Digital Twin would allow for additional information that may not be represented in shape or text form. This would increase the comprehensiveness of the data associated with each feature.
- Integration with existing systems: Improving connectivity and interoperability with other management programs and data sources would eliminate duplication of effort and provide a unified view of the data.
- Real-time data synchronization: Improving the ability to synchronize with real-time data sources would provide more accurate and timely information for decision making and analysis.
- Advanced analytics and forecasting capabilities: Incorporating advanced analytics techniques and predictive modeling capabilities would enable proactive maintenance, optimize resource allocation, and improve overall decision-making processes.
- User-friendly interfaces: Continually refining the user interface design and providing intuitive dashboards would improve the usability and adoption of the Digital Twin by various stakeholders.
- Representation of additional data: Adding more visual representations, such as colored pavements or presentation drawings, would provide a more realistic and comprehensive view of the digital model.

These additional improvements would enhance the functionality and value of the Digital Twin in areas such as data management, citizen engagement, and real-time information integration.

In addition, the presentation addressed the challenges associated with implementing and using the Digital Twin. These challenges included data integration and quality assurance, resource allocation for ongoing maintenance and updates, technical infrastructure requirements, and stakeholder engagement and training. Leaders were encouraged to openly discuss these challenges and offer suggestions for effectively addressing them.

Active participation was encouraged throughout the presentation, ensuring that all managers had the opportunity to voice their opinions and concerns. The session fostered a collaborative environment where constructive feedback was welcomed and valued.

While the managers of Weert's public space expressed their appreciation for the quality and capabilities of the Digital Twin, they also expressed skepticism about its implementation in the municipality. They questioned whether changes to workflows and tools would receive sufficient support, given past experiences.

Overall, the post-assessment presentation served as an important platform for the managers of the municipality of Weert to express their views on the usefulness of the Digital Twin. It allowed them to highlight areas for improvement and discuss the challenges associated with its implementation. The presentation facilitated a constructive dialogue and enabled the municipality to gather valuable insights and recommendations for improving the effectiveness of the Digital Twin in supporting urban planning and development in Weert.

TACKLING THE AREAS OF IMPROVEMENT

Further research and development is needed to implement these improvements in the Digital Twin. The ability to attach documents (Excel, Word, or PDF) to features would require the design and implementation of a document management system within the Digital Twin framework. This system would need to support file storage, retrieval, and indexing to allow users to associate relevant documents with specific features.

Improving integration with existing systems requires research into standardized protocols, data exchange formats, and APIs that facilitate seamless data sharing and interoperability. This research would involve identifying the key requirements and compatibility considerations to establish smooth connectivity between the Digital Twin and various management programs and data sources.

Improving real-time data synchronization would involve researching and implementing efficient data streaming mechanisms, event-driven architectures, and automated data ingestion processes. This would ensure that the Digital Twin remains synchronized with real-time data sources, providing accurate and timely information for decision making and analysis.

Incorporating advanced analytics and predictive capabilities will require the development and refinement of algorithms, statistical models, and simulation techniques specifically tailored to the context of the Digital Twin. This research would include exploring machine learning approaches, data mining techniques, and predictive modeling methods to enable proactive maintenance, resource optimization, and improved decision-making processes.

Continuous refinement of user interfaces and intuitive dashboards would require iterative design and user-centered research. Conducting usability studies, gathering feedback, and implementing design best practices would enhance the user experience and promote adoption of the Digital Twin by various stakeholders.

To display additional data, such as colored pavements or presentation drawings, research would focus on developing specialized visualization techniques and exploring technologies such as augmented reality or virtual reality. This would provide a more realistic and comprehensive view of the digital model, making it more engaging and informative for users.

Overall, implementing these improvements in the Digital Twin will require dedicated research and development efforts to refine the underlying technologies, design effective user interfaces, and establish seamless integration with existing systems. Continued research will be critical to realizing the full potential of the Digital Twin and its application in various domains.

6.8 CONCLUSION

In conclusion, the creation of the Digital Twin for Cities in the pilot area of Molenakker within the municipality of Weert was a significant undertaking. Through a combination of interviews with city managers and extensive research from relevant literature, a comprehensive framework for the construction of the Digital Twin has been developed.

The data collection process involved gathering various datasets, including 3D building data, terrain data, topographic data, infrastructure data, and geospatial imagery, from multiple sources, such as government agencies and the municipality itself. These datasets formed the basis for the construction of the Digital Twin.

The data processing steps outlined in Section 4.2 were meticulously carried out for the pilot area. The area of interest was defined, aerial imagery was collected and processed, LiDAR data was converted and analyzed to create a digital terrain model, and various elements such as buildings, bridges, sewers, utilities, trees, street lights, green spaces, roads, and water bodies were modeled and integrated into the Digital Twin.

The model creation process focused on optimizing performance by incorporating scale-dependent symbology. This approach ensured that the Digital Twin displayed relevant information based on the viewing scale, thereby improving efficiency and user experience.

Sensor data integration was also demonstrated in the pilot area, demonstrating the potential for real-time information collection and analysis. By accessing data from sensors through an API, the Digital Twin can provide valuable insights for decision making and proactive problem identification.

The ability to update and maintain the Digital Twin in real time was highlighted as a key feature. Mutations to the data can be made and applied to all instances of the Digital Twin, ensuring that information remains current and accessible to all stakeholders.

The visualization capabilities of the Digital Twin were demonstrated through a comprehensive display of information. Various layers and attributes were combined to provide a holistic view for specific expertise, such as the team responsible for green and waste management. This ability to consolidate and visualize information streamlines decision-making and facilitates effective collaboration.

The post-assessment presentation gathered feedback from municipality managers, including valuable suggestions for improvement. Challenges related to data integration, resource allocation, and stakeholder engagement were discussed. Ongoing research and development is needed to implement enhancements, including a document management system, improved integration, real-time data synchronization, advanced analytics, refined user interfaces, and visualization technologies. By incorporating these improvements and addressing the identified areas for improvement and challenges, municipalities can optimize the functionalities of the Digital Twin for urban planning and development. Research is essential to refine the underlying technologies, ensure seamless integration, and improve the user experience. The Digital Twin has the potential to provide valuable insights for decision-making in various fields, so further research and development efforts are essential to realize its full potential.

The creation of the Digital Twin for Cities in the pilot area of Molenakker, with the input and collaboration of the municipality's managers, represents a significant step forward in the use of technology and data for informed decision-making and sustainable urban development.

7 CONCLUSION AND RECOMMENDATIONS

Managing and planning the public space poses significant challenges for municipalities, ranging from diverse environmental entities such as roads, green spaces, and infrastructure. Outdated practices hinder efficient information management, but emerging technologies such as Building Information Modeling (BIM) and Geographical Information Systems (GIS) offer solutions. By combining BIM's shared 3D database with GIS, a 3D geospatial representation of the city's environmental entities can be achieved. In addition, Digital Twins, which continuously update virtual replicas with real-time data, optimize performance and efficiency. This study focuses on the development of a Digital Twin for the management of environmental entities in Weert, the Netherlands, providing an intelligent and dynamic representation of the physical environment. The Digital Twin enables different municipal disciplines to manage and share data, predict and simulate interventions, and support efficient asset management. Its implementation in urban contexts holds immense potential for incorporating building information into planning processes, improving stakeholder coordination, integrating smart technologies, and optimizing resource allocation. Despite challenges such as data accuracy and integration, the transformative power of Digital Twins in revolutionizing urban planning, construction, and infrastructure management is undeniable, promoting informed decision-making, optimized resource utilization, and sustainable urban environments.

7.1 CONCLUSION

In conclusion, the management and planning of public spaces is a major challenge for municipalities and requires a well-structured information management process. Digital Twins, virtual replicas of physical objects or systems, along with technologies such as Building Information Modeling (BIM) and Geographic Information Systems (GIS), have emerged as promising solutions for managing the built environment.

Digital Twins offer numerous benefits in various fields, including urban planning, construction, and infrastructure management. They provide opportunities for improved decision making, resource optimization, and integration of smart technologies. By integrating sensors into urban Digital Twins, real-time monitoring, analysis, and control become possible, leading to informed decision-making and improved quality of life for residents.

The case study of the municipality of Weert in the Netherlands illustrates the practical application of Digital Twins for managing environmental entities in public space. Interviews with managers provided valuable insights into their data management practices and expectations regarding Digital Twins. The implementation of Digital Twins in the pilot area of Molenakker served as a testbed for refining the technology and establishing best practices.

The construction of a Digital Twin for the management of environmental entities in the public space involves several stages, including data collection, processing, model creation, integration, updating, and visualization. Accurate and dynamic representations of the public realm are created through the use of feature data and real-time sensor data. The process emphasizes the importance of data accuracy, integration, and continuous updating to reflect changes in the environment.

Effectively managing and using data in a Digital Twin implementation requires a robust system architecture. ArcGIS software, such as ArcGIS Pro and ArcGIS Online, provides features and support that facilitate data collection, integration, cloud infrastructure, data management, visualization tools, data analysis, connectivity protocols, security measures, and scalability. These tools provide municipalities with efficient data management capabilities.

In summary, Digital Twins have the potential to revolutionize urban planning, construction, and infrastructure management. By creating digital representations of physical assets and integrating real-time data, cities can make informed decisions, optimize resource utilization, and improve the overall efficiency of public space management. The use of Digital Twins, along with complementary technologies, can pave the way for smarter and more sustainable cities in the future.

7.2 FUTURE RESEARCH RECOMMENDATIONS

Based on the conclusions reached, this research offers the following recommendations for future research regarding the management of environmental entities of the public space using Digital Twins.

- Privacy preserving techniques: Investigate and develop privacy-preserving techniques for Digital Twins that manage environmental entities in the public domain. Explore methods such as data anonymization, differential privacy, secure multi-party computation, and encryption to ensure the protection of sensitive data while enabling effective analysis and decision making. Consider the legal and ethical implications of privacy in the context of environmental entity management.
- Stakeholder engagement strategies: Conduct research on effective stakeholder engagement strategies in Digital Twins for environmental entity management. Investigate methods for engaging diverse stakeholders, such as residents, policy makers, environmental organizations, and industry representatives, in the design, implementation, and decision-making processes. Develop frameworks and tools to facilitate collaboration, consensus building, and inclusive participation in environmental management initiatives through Digital Twins.
- Simulation and prediction models: Explore advanced simulation and prediction models within Digital Twins to support the management of environmental assets in the public space. Develop realistic and accurate models that can simulate the behavior of environmental factors such as air quality, noise pollution, energy consumption, and waste management. These models can help stakeholders understand the environmental impacts of different interventions, policies and urban planning strategies, enabling informed decision making and sustainable management.
- Big data analytics: Explore methods for effectively analyzing and using big data within Digital Twins to manage environmental entities. Develop scalable algorithms and techniques to process and analyze large volumes of heterogeneous data from diverse sources such as sensors, satellite imagery, social media, and public records. Explore data fusion approaches to integrate and correlate data from multiple domains to gain comprehensive insights into the environmental factors affecting the public space.
- Validation and performance evaluation: Develop robust validation and performance evaluation methods for Digital Twins in environmental asset management. Create standardized approaches to validate the accuracy and reliability of simulation models, predictive algorithms, and real-time data integration. Evaluate the performance of Digital Twins in terms of their ability to support informed decision making, optimize resource allocation, and achieve sustainability goals. Consider both technical aspects and socio-economic and environmental dimensions in the validation process.

By addressing these research areas, future studies can contribute to the advancement of Digital Twins for the management of environmental entities in the public space. These recommendations can help ensure privacy protection, effective stakeholder engagement, accurate simulations, use of big data, and reliable validation to enable sustainable management of the public environment through Digital Twins.

7.3 MANAGEMENT RECOMMENDATIONS

Based on the conclusions reached, this research offers the following recommendations for the municipality of Weert and other municipalities interested in developing Digital Twins:

- Establish an information management process: Develop a well-structured information management process specifically tailored to the management of public spaces. This process should incorporate Digital Twins, BIM and GIS technologies to enable effective data collection, integration and analysis.
- Invest in Digital Twin implementation: Recognize the potential benefits of Digital Twins for managing environmental assets in public spaces and consider implementing them on a larger scale. Learn from the pilot project in Molenakker and refine the technology based on established best practices.
- Improve data management practices: Emphasize the importance of accurate and dynamic data representations in Digital Twins. Focus on data accuracy, integration, and continuous updating to ensure that digital replicas reflect real-time changes in the environment.
- Build a robust system architecture: Implement a robust system architecture that supports the management and use of data in Digital Twin implementations. Consider using high-end software packages, to facilitate data collection, integration, visualization, and analysis, and to ensure scalability, connectivity, and security.
- Encourage collaboration and stakeholder engagement: Encourage collaboration among relevant stakeholders, including city officials, planners, engineers, and community members, to ensure successful implementation and use of Digital Twins. Engage stakeholders in the design, implementation, and decision-making processes to achieve inclusive and sustainable outcomes.
- Promote training and knowledge sharing: Provide training and knowledge sharing opportunities for community staff to increase their understanding of Digital Twins and related technologies. This will enable them to effectively use the capabilities of these technologies in managing public spaces and making informed decisions.

By implementing these recommendations, municipalities can harness the potential of Digital Twins to revolutionize urban planning, construction and infrastructure management. This will lead to improved decision making, optimized resource utilization and increased efficiency in the management of public spaces. Ultimately, it will contribute to the creation of smarter and more sustainable cities for the future.

7.4 CRITICAL REVIEW

The research on Digital Twins for the management of environmental entities of public space offers valuable insights, but certain limitations need to be addressed. Due to time and knowledge constraints, not all wishes and requirements expressed in the interviews could be implemented, which may have limited the comprehensiveness of the findings. In addition, the author faced challenges in implementing all collected sensors due to external stakeholder paywalls, which limited the availability of critical data for analysis. Furthermore, there was limited research conducted for the parking team, due to the defined scope of the study and limitations in data availability.

These limitations raise concerns about the completeness and validity of the research findings, as certain aspects and perspectives may not have been adequately captured. It is critical that future studies address these limitations by more fully incorporating stakeholder expectations, finding alternatives to accessing sensor data from external sources, and expanding research coverage to areas such as parking management to ensure a more holistic understanding.

Given these limitations, caution should be exercised in interpreting and applying the research findings to real-world scenarios. Further research efforts should aim to address these challenges, as overcoming them will enhance the practicality and applicability of Digital Twins in effectively managing environmental entities of the public space.

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APPENDIX I –INTERVIEWS

This appendix shows the questions and answers from the interviews in more detail.

TABLE OF CONTENTS

PROGRAM DIRECTOR

ROAD INFRASTRUCTURE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am a budget holder for road infrastructure, traffic, and civil engineering structures, and I supervise the maintenance

2 - What data do you manage/are you responsible for?

- I do not manage any data myself, but I am responsible for the management of data by the functional manager.

3 - Where is this data stored and in what format?

- We, as the program Road Infrastructure, mostly store Shapefile data on servers of Sweco. Personally, my Excel/word documents are stored on the Explorer of the municipality of Weert.

4 - What tools do you use to manage/view this data?

- We, as the program Road Infrastructure, mostly use Obsurv for managing data. Personally, I use Kaartviewer, since I only have to view data. In addition, I use Excel for maintenance plans and Google Streetview/Cyclorame for checking traffic situations in the public space.

5 - What tasks do you perform to manage the data with these tools?

- I do budget management in Excel mostly.

6 - Are you using sensors to collect additional data in real time?

- At this point, we don’t have any sensors in use, however, sometimes per year we do traffic calculations using sensors.

7 - If so, what tool do you use to query this data?

- In most cases, we get the data in .csv format, so we use Excel to query the data.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, this would greatly improve the integrality of the different programs.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, however, data has to be correct and complete. It will show the required data more easily.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Predicting maintenance of roads and civil engineering structures. Consulting historic traffic counts more easily

ADDITIONAL REMARKS

- Obsurv data is not up-to-date
- We would like to add documents to objects in Obsurv

FUNCTIONAL MANAGER

ROAD INFRASTRUCTURE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am a manager of roads and civil engineering structures.

2 - What data do you manage/are you responsible for?

- I manage and create maintenance plans for roads and civil engineering structures based on current and expected conditions.

3 - Where is this data stored and in what format?

- The data containing all the attributes from the roads and civil engineering structures in Shapefile format is located on the servers of Sweco and the documents holding information about maintenance plans and conditions are located in the folders on the explorer of the municipality of Weert.

4 - What tools do you use to manage/view this data?

- I mostly use Kaartviewer to view the GIS data, however, when I have to do mutations to the data I use Obsurv. I use Excel for creating and editing maintenance plans.

5 - What tasks do you perform to manage the data with these tools?

- I change attribute data of certain features in Obsurv whenever changes have been made in the public space. In addition, I change the planning of maintenance in Excel.

6 - Are you using sensors to collect additional data in real time?

- At this point, we don’t have any sensors in use, however, sometimes per year we do traffic calculations using sensors.

7 - If so, what tool do you use to query this data?

- In most cases, we get the data in .csv format, so we use Excel to query the data.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, but only if reconstructions or new projects are required, where we have to check for nearby environment entities from different teams.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, it gives a better and more clear impression of the public space compared to 2D maps or drawings. In addition, it would greatly improve the editing process.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Predict future maintenance needs, calculate free space for large road transport, view historical data from public space

ADDITIONAL REMARKS

DIRECTOR

ROAD INFRASTRUCTURE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?
- I am responsible for the Financial settlement of projects and connections with contractors.

2 - What data do you manage/are you responsible for?
- I manage financial data of several projects and construction works.

3 - Where is this data stored and in what format?
- I store all of my data internally on the server of Weert.

4 - What tools do you use to manage/view this data?
- Mostly Excel for financial data, but also Kaartviewer, Streetview/Cyclorama, and AutoCAD for viewing data.

5 - What tasks do you perform to manage the data with these tools?
- I only use the tools for viewing data, and Excel for doing calculations.

6 - Are you using sensors to collect additional data in real time?
- I do not collect any data using sensors.

7 - If so, what tool do you use to query this data?
- N/A

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?
- Yes, it would decrease the search time I need for consulting different information

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?
- Yes, it visualizes the data more easily

10 - What additional expectations do you have of a Digital Twin for public space management?
- Analyse data on notifications of problem locations, to prevent future problems

ADDITIONAL REMARKS

PROGRAM DIRECTOR

WATER & SEWERAGE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am the Program Director of Water & Sewerage, directing people on the content of the work.

2 - What data do you manage/are you responsible for?

- I only manage cost key figures, however, I am responsible for the other Water & Sewerage managers' work.

3 - Where is this data stored and in what format?

- We, the program Water & Sewerage, store most of our data on servers of Sweco, which make it available in tools like Obsurv/RioGL. This data is all in GIS format. I store my cost key figure data in Excel.

4 - What tools do you use to manage/view this data?

- I mostly use RioGL for consulting sewerage data, this tool also allows for mutations.

5 - What tasks do you perform to manage the data with these tools?

- I personally do not perform any tasks to manage GIS data, however, I do make mutations to cost key figures in Excel.

6 - Are you using sensors to collect additional data in real time?

- We do have sensors that collect data on sewerage systems, however, this data is managed by an external party, in this case, WBL (Waterschapsbedrijf Limburg).

7 - If so, what tool do you use to query this data?

- We collect reports from WBL, not the data itself.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, but only if the data is complete and correct from all teams.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, it would make consulting and managing data more efficient since a lot of data can be viewed at a glance. In addition, collecting sensor data will make predictions more precise.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Flooding simulation, predicting problems in the infrastructure.

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

WATER & SEWERAGE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?
- I advise colleagues on tasks regarding Water & Sewerage including policies and procedures.

2 - What data do you manage/are you responsible for?
- I manage data on sewer lines, connecting sewers, gullies, special prevision sewers, pumping stations, surface waters, and ditches.

3 - Where is this data stored and in what format?
- We store most of our GIS data at Sweco, however, we do store some of our data locally at the municipality of Weert, these are mostly inspection reports and related videos.

4 - What tools do you use to manage/view this data?
- I use RioGL/Obsurv for managing main sewerage components, Kikker for gullies, RioX for connecting sewers, and Kaartviewer for consulting this data in relation to other entities.

5 - What tasks do you perform to manage the data with these tools?
- I do some small mutations to some of the components, however, most of this is done by an external party in RioGL. In RioX and Kikker I check revisions and status updates.

6 - Are you using sensors to collect additional data in real time?
- We have an external party, WBL (Waterschapsbedrijf Limburg), that collects data on monitoring wells, groundwater levels, and water levels.

7 - If so, what tool do you use to query this data?
- We collect reports from WBL, not the data itself.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?
- Yes, it would greatly decrease the time that is required for consulting other teams' information.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?
- Yes, combining all data in one location that can be consulted in 3D will drastically reduce the time it takes to respond to questions from third parties

10 - What additional expectations do you have of a Digital Twin for public space management?
- Maintenance prediction and simulation of the amount of water on the streets after certain rainfalls.

ADDITIONAL REMARKS

PROGRAM DIRECTOR

GREEN & WASTE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am the Program Director of Green & Waste, where I direct people on the content of their work.

2 - What data do you manage/are you responsible for?

- I do not manage any data, however, I am responsible for the data that our team manages. This includes greenery, trees, and containers.

3 - Where is this data stored and in what format?

- We, the program Green & Waste, store most of our GIS data on servers of Sweco.

4 - What tools do you use to manage/view this data?

- We mostly use Obsurv for the management of our data, however, we mostly consult data, since mutations are done by Sweco. Therefore, many of us use Kaartviewer, since it is easier to use.

5 - What tasks do you perform to manage the data with these tools?

- I personally do not perform any tasks to manage any of the data we are responsible for.

6 - Are you using sensors to collect additional data in real time?

- We do have sensors in the public space that collect data on greenery, including humidity, temperature, and water levels, however, this is all hosted by Attender Groen.

7 - If so, what tool do you use to query this data?

- We can consult this data from the website of Attender Groen.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, to check for collisions with other teams, for example, when we want to plant new trees.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, It would make mutations & visualizations easier, however, those mutations that are done in the work field should be checked by a functional director for the correctness

10 - What additional expectations do you have of a Digital Twin for public space management?

- Predicting or advising on maintenance measures or street types based on combining data of historic maintenance and current types

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

GREEN

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am a Functional manager Green, managing green environmental entities in the public space, including trees and playgrounds

2 - What data do you manage/are you responsible for?

- I manage data on greenery, trees, playgrounds, and recreation facilities.

3 - Where is this data stored and in what format?

- We mostly store our data in the program Obsurv, so that means externally at Sweco. This is mostly GIS data.

4 - What tools do you use to manage/view this data?

- We mostly use Obsurv for the management of our data, however, we mostly consult data, since mutations are done by Sweco. For tree management we use DigiTree, this GIS-based viewer can show us the important information we need. For other greenery types, we use GAS.

5 - What tasks do you perform to manage the data with these tools?

- I personally only make exports in these tools to make calculations or maintenance plans in Excel.

6 - Are you using sensors to collect additional data in real time?

- We have sensor data on humidity, temperatures, and salt levels of different greenery types.

7 - If so, what tool do you use to query this data?

- We can consult this data from a dashboard on the website of Attender Groen.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, to check for collisions with other environmental entities when, for example, placing trees.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, it would greatly improve management possibilities and gather all data in one portal.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Yes, predicting tree growth or maintenance expectancy.

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

WASTE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?
- I am a Functional manager of Waste & city cleaning.

2 - What data do you manage/are you responsible for?
- I manage data on waste management, including containers and ice management during winter.

3 - Where is this data stored and in what format?
- I store my data in Obsurv & Excel, the Obsurv data is GIS and is stored by Sweco.

4 - What tools do you use to manage/view this data?
- I mostly use CMS van Bammes & Relion for viewing waste data.

5 - What tasks do you perform to manage the data with these tools?
- I mostly only make changes to routes for ice management since the containers are managed by external parties.

6 - Are you using sensors to collect additional data in real time?
- We have sensors that collect data on snowfall and road temperatures during winter. In addition, we also have fill levels for our underground containers.

7 - If so, what tool do you use to query this data?
- We use dashboards from different parties to view this data.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?
- Yes, for placing or renewing containers

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?
- Yes, if all the third-party data is viewable to the full extent.

10 - What additional expectations do you have of a Digital Twin for public space management?
- Predicting waste collection frequencies

ADDITIONAL REMARKS

DIRECTOR

GREEN & WASTE

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am a Director of Green & Waste, supervising the maintenance of greenery and waste collection

2 - What data do you manage/are you responsible for?

- I manage notifications of problems regarding Green & Waste in the public space

3 - Where is this data stored and in what format?

- I store notification data in Apptimize, while all other GIS information from the team is stored externally at Sweco. All other documents are stored internally at the server of Weert.

4 - What tools do you use to manage/view this data?

- I use Kaartviewer for viewing team data and Apptimize to manage the notification data.

5 - What tasks do you perform to manage the data with these tools?

- I consult historic data to optimize planning, consult sensors to check the state of greenery, check for notification regarding greenery or waste, and consult reports of maintenance

6 - Are you using sensors to collect additional data in real time?

- We do have several sensors in use, mostly for checking humidity, temperatures, and salts levels of greenery, but also for fill levels of containers.

7 - If so, what tool do you use to query this data?

- We use dashboards from different parties to view this data.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, this would make it a lot easier to check for example if tree planting would collide with other infrastructures

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Consulting and managing data would be a lot easier using a Digital Twin since it requires fewer steps and shows more information.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Future growth of trees and the impact it would have on the streetscape and checking for root collision with cables and pipes

ADDITIONAL REMARKS

- Obsurv is hard to use and limited in possibilities
- It would be nice to have notifications of inhabitants, directly in the Digital Twin model
- Let the model advise us on greenery types

PROGRAM DIRECTOR

PARKING

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am the Program Director of Parking, this makes me responsible for the work that is conducted by our team and the data we use.

2 - What data do you manage/are you responsible for?

- We, as the team Parking, manage data of Parking garages, parking permits, and charging stations for e-vehicles.

3 - Where is this data stored and in what format?

- The locations of parking spaces are stored in GIS format using Sweco's Obsurv application, other data is stored locally on the network of the municipality of Weert.

4 - What tools do you use to manage/view this data?

- For location data we use Obsurv, but for the other data, we tend to use several different programs for gathering different information.

5 - What tasks do you perform to manage the data with these tools?

- I personally do not perform any tasks to manage any of the data we are responsible for, however, our team mostly makes mutations to user data, whenever they get or get rid of a parking permit.

6 - Are you using sensors to collect additional data in real time?

- We have sensors in our parking garages that monitor the occupancy rates, in addition, the charging stations show information on charging times, power use, and how long vehicles park there.

7 - If so, what tool do you use to query this data?

- We can consult this data from different web portals, such as Parking IP

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Yes, to get a better understanding of the situation at a certain location.

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, it would make it much easier for us to visualize data, since we now have to use multiple web portals.

10 - What additional expectations do you have of a Digital Twin for public space management?

- Predicting parking occupancy rates in normal situations, but most important during specific events regarding road closures.

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

TECHNICAL INSTALLATIONS

QUESTIONS & ANSWERS

1 - What is your role within the municipality of Weert?

- I am a functional manager of Technical Installations, managing all environmental entities that are connected to a power grid, except pumps.

2 - What data do you manage/are you responsible for?

- I manage data on Streetlighting, drive-through bollards, and traffic lights/VRIs (VerkeersRegelInstallatie).

3 - Where is this data stored and in what format?

- The data on streetlights is stored in Obsurv, while other data is stored externally at partners or just on the internal server of Weert.

4 - What tools do you use to manage/view this data?

- I mostly use Luminer for consulting streetlight data, Parkbase for drive-through bollards, Liteweb for other installations, and GRIP for all others.

5 - What tasks do you perform to manage the data with these tools?

- Mostly changing attribute data of streetlighting

6 - Are you using sensors to collect additional data in real time?

- We collect sensor data on street lighting.

7 - If so, what tool do you use to query this data?

- We have a dashboard from an external party to view this data.

8 - Would you benefit from having at-a-glance access to data from other teams as well as your own?

- Not much, only for projects

9 - Based on what you've just learned about Digital Twins, do you think a Digital Twin could make your work easier/more efficient?

- Yes, mostly for consulting sensor data and mutating data of entities

10 - What additional expectations do you have of a Digital Twin for public space management?

- N/A

ADDITIONAL REMARKS

APPENDIX II – SENSOR INTEGRATION

As mentioned in the thesis, the sensors are integrated using an API that is executed using Python. Below is the code that was used in Visual Studio Code to request information from the JSON API.

```python
from datetime import datetime, timedelta
import requests

def authenticate(username, password):
    url = "https://app.connectedgreen.nl/api/Account/Authenticate"
    headers = {
        "Content-Type": "application/json"
    }
    data = {
        "userName": username,
        "password": password,
        "acceptedTermsOfUsage": True
    }

    response = requests.post(url, json=data, headers=headers)
    response.raise_for_status()

    json_data = response.json()
    access_token = json_data["accessToken"]

    return access_token

def get_all_sensors_by_projectId(bearer_token, projectId = 485):
    url = "https://app.connectedgreen.nl/api/Sensor/FilterList"
    headers = {
        "Authorization": f"Bearer {bearer_token}",
        "Content-Type": "application/json"
    }
    data = {
        #ProjectId of Weert (485)
        "ProjectId": projectId
    }

    response = requests.post(url, json=data, headers=headers)
    response.raise_for_status()

    json_data = response.json()

    print(json_data)

    return json_data
```

```python
def get_sensorReadings_by_sensorIds(sensorIds, from_date, to_date):
    url = "https://app.connectedgreen.nl/api/SensorReading/List"
    headers = {
        "Authorization": f"Bearer {bearer_token}",
        "Content-Type": "application/json"
    }
    data = {
        "sensorIds": sensorIds,
        "sensorPartIds": [1],
        "fromDateTime": from_date,
        "toDateTime": to_date
    }

    response = requests.post(url, json=data, headers=headers)
    response.raise_for_status()

    json_data = response.json()

    print(json_data)

    return json_data

# Credentials
username = "n.kamphuis@weert.nl"
password = "*************"

bearer_token = authenticate(username, password)

projectId = 485

sensors = get_all_sensors_by_projectId(bearer_token, projectId)

to_date = datetime.utcnow()

from_date = to_date - timedelta(days=7)

sensorIds = [1732, 1730]

sensorReadings = get_sensorReadings_by_sensorIds(sensorIds,
from_date.strftime("%Y-%m-%dT%H:%M:%S.%fZ"), to_date.strftime("%Y-%m-
%dT%H:%M:%S.%fZ"))
```

APPENDIX III – THE DIGITAL TWIN

Visualizing the Digital Twin using screenshots is limiting and does not justify the model itself. Therefore, a shared link is created so that any user can view and edit the model.

INSTRUCTIONS

Users can open the following link using any client: **https://arcg.is/1CbzOm0**

If a login prompt is shown, please use the following account to log in if you don't have an ArcGIS account already:

USERNAME: n.kamphuis_tueeindhoven

PASSWORD: DigitalTwins2023!

The following screen should appear on Desktop & Mobile clients respectively:

REMARKS

There is a possibility that some layers are not shown properly or do not show at all, this is the result of protected data that cannot be shown publicly.

Feel free to make edits or turn layers on or off since the integrity of the model is not a priority.

If you have any questions regarding the model or don't see the screens shown above, please contact me using email (n.kamphuis@student.tue.nl) or by phone (06-23973326).

APPENDIX IV – POST-ASSESEMENT

This appendix shows the questions and answers from the post-assesment in more detail.

TABLE OF CONTENTS

FUNCTIONAL MANAGER

ROAD INFRASTRUCTURE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - Think so, but then it must be fully equipped

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - Yes the integrality between the teams is much better.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - Yes it does, the 3D visualization gives a much clearer picture in comparison to our current 2D programs.

4. **Is mutating data simpler in the Digital Twin?**
   - Yes, because it requires less steps than our current program.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - Construction of pavements, in multiple layers, however, we do not have that now on obsurv either.
     Add (links to) documents, such as soil surveys, asphalt surveys, delivery notes, etc.

ADDITIONAL REMARKS

DIRECTOR

ROAD INFRASTRUCTURE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - Yes, the advantage in this model is that you yourself can (easily) set up a so-called passport to retrieve data that are important to the person. The data comes from the management programs of the functional managers sewerage, green and Infra.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - I would not say better because the data are identical from a management programman the advantage concerns the individual choice which each person can make.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - It is clearly displayed and speaks more for itself in 3D , so this is more pleasing. Again, this is persona.

4. **Is mutating data simpler in the Digital Twin?**
   - I can't judge that, however, Changes should only be possible by an administrator or data manager and should be properly protected from users who are only allowed to consult.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - Right now I am not missing any relevant data data from objects and now may be the opportunity to work with the functional manager to catch up and set up a work process that we can start working on together.

ADDITIONAL REMARKS

Thank you for your personal presentation of the model you developed to access public space data. Given my former position as a public space manager in another municipality, this model immediately appeals to me and I find it very interesting. In my current position as a superintendent, we regularly need to consult data about the situation outside.

The presented model in 3D gives a clear picture and is visually understandable for (not) everyone. By being able to switch the layers on or off in a convenient way, this is even more user-friendly for the user and everyone can play with it as they like it. As you indicate, each user can create his own settings. By clicking on the appropriate road section parts or sewer surfaces, the data can be quickly accessed. The data are displayed in a clear passport and, if desired, can also be modified again by adding certain fields. I did notice the various colors of the relevant road sections, green areas, planting and trees. And the underground infrastructure of cables and pipes. These can also be easily selected from the various colors.

PROGRAM DIRECTOR

WATER & SEWERAGE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - I tried it on my iPad. On that, I still don't find it very useful. But maybe I can use it better on a normal "Windows" PC. To really say whether it works better than a management program I can't say. I have too little experience with a management program for that.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - The integrality seems much better at first. You can see the coherence.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - This depends entirely on the information you need. Should you need to convert to a 2D design, it is useful to see numbers. With sewers, for example, think of b.o.b. and diameter. I have too little knowledge and knowledge of the Digital Twin to be able to determine whether this is also easily possible / visible.

4. **Is mutating data simpler in the Digital Twin?**
   - I can't judge that.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - Representation of, for example, color pavements so as to create a representation that it could be in "reality." So a kind of presentation drawing. That would then make an aerial photograph (almost) unnecessary.

ADDITIONAL REMARKS

In general, I think there is much more possible than I know / can know right now. Besides, I only looked at it with the iPad and that is more difficult to use and assess anyway.

Good luck with your thesis and I would really love to be able to do more with this as an organization in the future. This is a very nice challenge from which you, as a data manager, may be able to derive much more energy in the future. You can bring a lot to our organization and I hope that you will do so and that you will get the opportunity to do so. I am sure we will get together to talk about this.

FUNCTIONAL MANAGER

WATER & SEWERAGE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - The Digital Twin is simpler and more efficient than our current management program for water and sewerage systems.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - With the Digital Twin, data access is much more convenient, allowing for seamless access within our team and across departments.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - The Digital Twin clearly and intuitively displays data, providing a comprehensive view of our water and sewer infrastructure.

4. **Is mutating data simpler in the Digital Twin?**
   - With its user-friendly interfaces and efficient data management capabilities, the Digital Twin makes data mutation easier.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - Integrating with other systems, incorporating advanced analytics and predictive capabilities, and refining the user experience are all areas for improvement.

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

GREEN

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**

- The Digital Twin provides a more streamlined and efficient approach to managing green entities, making it an advantageous option from a green perspective.

2. Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?

- Data accessibility is greatly improved with the Digital Twin. It provides seamless access to data, both within our team and across departments. This improved accessibility promotes better collaboration and coordination between teams.

3. Does the Digital Twin display the data more clearly than your current management/consulting program?

- The Digital Twin excels at presenting data in a clear and intuitive manner. Its visualizations and interactive features make it easier to analyze and interpret information related to the performance and status of green assets.

4. Is mutating data simpler in the Digital Twin?

- Modifying or updating data is made easier within the Digital Twin. With its efficient data management capabilities, making changes and updates is a straightforward process. This flexibility allows us to respond quickly to changing needs and circumstances.

5. What are you still missing from this Digital Twin? Do you see any areas for improvement?

- Further integration with existing systems, such as data sources and management platforms, would enhance its functionality and reduce duplication of effort. In addition, improving real-time data synchronization and providing more user-friendly interfaces would improve the overall user experience and usability of the Digital Twin. These improvements would contribute to its effectiveness as a management tool.

ADDITIONAL REMARKS

FUNCTIONAL MANAGER

WASTE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - I have little experience with our current management tools, however, it does look promising.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - Same as the first question

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - I can't really compare it since I mostly work with Excel for managing the waste data, however, the 3D visualization gives a good representation.

4. **Is mutating data simpler in the Digital Twin?**
   - I can't judge that, however, it looks easy.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - I don't have any at the moment

ADDITIONAL REMARKS

In general, I think there is much more possible than I know / can know right now. Besides, I only looked at it with the iPad and that is more difficult to use and assess anyway.

Good luck with your thesis and I would really love to be able to do more with this as an organization in the future. This is a very nice challenge from which you, as a data manager, may be able to derive much more energy in the future. You can bring a lot to our organization and I hope that you will do so and that you will get the opportunity to do so. I am sure we will get together to talk about this.

DIRECTOR

GREEN & WASTE

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - Yes, this orients easier and is much faster and intuitiver

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - See 1, yes it seems to be the case.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - From what I can tell, yes

4. **Is mutating data simpler in the Digital Twin?**
   - Yes, you showed me this

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - For example, i would really like to see the notifications at address level.

ADDITIONAL REMARKS

PROGRAM DIRECTOR

PARKING

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - From parking management, we are not yet using a management system.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - It is a fast and accessible program I do notice. Geoviewer takes longer to start up!

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - Not applicable.

4. **Is mutating data simpler in the Digital Twin?**
   - I can't judge that.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - From a parking perspective, I would like to see the following in the distant future:
     - Electric charging stations in public spaces (perhaps with real-time information on whether they are being used)
     - Parking spaces drawn in separately. This might allow you to use a tool to see how many parking spaces are in the public space.
     - You can then use this in turn to perform parking pressure measurements (counts by a company how many cars are parked).
     - Real-time information on parking garage occupancy rates.

ADDITIONAL REMARKS

In general, I think there is much more possible than I know / can know right now. Besides, I only looked at it with the iPad and that is more difficult to use and assess anyway.

Good luck with your thesis and I would really love to be able to do more with this as an organization in the future. This is a very nice challenge from which you, as a data manager, may be able to derive much more energy in the future. You can bring a lot to our organization and I hope that you will do so and that you will get the opportunity to do so. I am sure we will get together to talk about this.

FUNCTIONAL MANAGER

TECHNICAL INSTALLATIONS

QUESTIONS & ANSWERS

1. **Do you think this Digital Twin works simpler than your current management/counseling program?**
   - Yes, the Digital Twin is simpler and more efficient than our current management/consulting program. It provides a streamlined approach to managing technical assets, making tasks easier to perform and understand.

2. **Is data accessibility (both your own and other teams') more convenient when using this Digital Twin?**
   - Absolutely! Data accessibility is much more convenient when using the Digital Twin. It allows seamless access to data, both within our own team and across departments. This improved accessibility promotes better collaboration and decision making.

3. **Does the Digital Twin display the data more clearly than your current management/consulting program?**
   - The Digital Twin excels at presenting data in a clear and intuitive manner. Its visualizations are highly effective in presenting information about the current state and performance of our technical assets. This clarity enhances our understanding and enables faster, more informed decision-making.

4. **Is mutating data simpler in the Digital Twin?**
   - Yes, changing data is easier in the Digital Twin. With its user-friendly interface and efficient data management capabilities, modifying and updating data is a seamless process. This ease of data manipulation contributes to a more agile and responsive management approach.

5. **What are you still missing from this Digital Twin? Do you see any areas for improvement?**
   - One area that could be enhanced is integration with existing data systems to ensure seamless connectivity and avoid duplication of effort. In addition, incorporating advanced analytics and predictive capabilities could further optimize our decision-making processes. Finally, a continued focus on user experience and interface refinement will ensure that the Digital Twin remains user-friendly and accessible to all stakeholders.

ADDITIONAL REMARKS

Overall, the Digital Twin holds great promise for improving the management of technical assets, but careful implementation, evaluation, and ongoing refinement are required to fully realize its benefits.