Rotterdam School of Management
Erasmus University

Master Thesis

Towards Self-Regulation in Cities

A Holistic Approach to Urban Digital Twin Design

Insights from Design Science Research

A Master Thesis

By

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Part of the program Business Information Management

Submitted to Rotterdam School of Management, Erasmus University

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Submitted on Thursday, June 20th, 2024

To be Defended on Thursday, June 27th, 2024, at 13:00

RSM - a force for positive change

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Preface and Acknowledgments

Before you lies the master thesis “Towards Self-Regulation in Cities: A Holistic Approach to Urban Digital Twin Design”. I wrote this thesis to finish my master's program in business information management at Erasmus University Rotterdam's Rotterdam School of Management. I researched and wrote this thesis from January to June of 2024.

During this thesis, I explored a topic in which I am very interested. For some years, the topic of a smart and sustainable world has been on my mind. I have always been captivated by the prospect of steering society towards a smart and sustainable future. I hope that with this thesis I can contribute to this goal. In this thesis, I will take you on a journey into the world of urban digital twins, a technology I believe can help cities achieve a smart and sustainable future.

I want to express my deepest gratitude to my thesis supervisor, Haydee Sheombar; without her guidance, this process would have been a lot harder. Her mentorship throughout this process has been invaluable. I also thank my co-reader, Eric van Heck, for his invaluable feedback and expertise.

I am also grateful to my fellow students and friends for making the last few years so fun; it would have been very boring to study alone. And finally, I would like to thank my family, who have always been there for me since day one. Without you, all of this would not have been possible.

The journey to complete this thesis was long and challenging, but ultimately very rewarding. I hope the following pages offer insight and inspire you to fight for a sustainable future.

Pelle Knegjes

Rotterdam, 2024

Executive Summary

This paper explores the concept of self-regulation in cities through the creation of a holistic Urban Digital Twin (UDT) design, termed CityOS. This research adopts the Design Science Research (DSR) methodology to develop a system design that integrates digital twin technology and smart city principles, aiming to achieve balance in the city's ecosystem.

The main research question addressed is: *How does a holistic approach to urban digital twin design enable the self-regulation of a smart city?*

To answer this question this paper presents a high-level design for CityOS a holistic approach to urban digital twins. The design is created based on 41 design choices which were gathered through academic literature, desk research, and expert interviews. The findings suggest that a holistic approach to UDT design significantly enhances a city's ability to manage and adapt its operations in real-time through data and simulations, also known as self-regulation. The proposed CityOS includes the following parts.

Meta-Architecture: This provides a high-level blueprint and shared vision of the system including the context, goals, scope, stakeholders, and architectural strategy. The meta-architecture ensures that all design efforts are aligned with the goals of the system and can be communicated to all stakeholders. The main design choices were that CityOS can be seen as the city's central nervous system, a system where the city's collective intelligence comes together enabling self-regulation to achieve urban homeostasis. Its primary goal is to unify the city ecosystem so that cities become self-regulated. Its main stakeholders are the public organizations, citizens & communities, academia, and private organizations of the city. The strategy suggests following the principle of 'form follows function' to reflect the dynamic nature of the city. It is suggested that CityOS adopt a hybrid configuration of centralized, decentralized, and distributed systems deployed across physical and digital dimensions.

Ecosystem-Driven Components: This highlights that the system should be a collaborative, open, and modular system that harnesses the collective intelligence of the city's ecosystem. This is achieved, first, through creating the system as a living lab allowing for co-development and co-creation. Second, by making the system accessible to all stakeholders to allow for the development of unique use cases. Third, by decentralizing governance through a governance board with representatives from all stakeholder groups to ensure that the system is used responsibly.

Self-Regulation: Shows how CityOS utilizes real-time data and simulations to enable proactive decision-making, supporting strategic, tactical, and operational decisions. It demonstrates CityOS' potential to autonomously manage city operations. Additionally, it showcases how CityOS can be used for evidence-informed decision-making in strategic and tactical decisions. CityOS can enable self-regulation in the city by providing decision-

makers with real-time data and simulations through the use of predictive and prescriptive digital twins. For strategic and tactical decisions the decision maker will still be a human who decides whether to use the prescribed interventions or not. For most operational decisions, they can be taken autonomously because they require less human accountability.

Additionally, the component shows that CityOS should be able to collect heterogeneous data from both the physical reality and the social reality through different data collection methods. It shows that data should be collected and stored as efficiently as possible to not waste system processing power. Moreover, it shows that the system should only collect data when an entity changes to prevent data clutter. Additionally, it shows that CityOS should ensure that collected data is from trusted sources and of high quality. Lastly, it highlights the need to balance data openness with privacy to prevent misuse and protect individuals.

Challenges identified include the implementation costs, significant resource requirements, and the need for high-quality and complete data. Implementation and adoption of the system should be gradually starting with local pilots and expanding over time.

This research concludes that a holistic approach to urban digital twin design enables the self-regulation of a smart city by unifying all city systems into an ecosystem-driven platform that allows for the real-time adaption and management of operations based on data and simulations.

Table of Contents

List of Figures

List of Tables

1 Introduction

In the past decades, profit-maximizing economies have fallen short within the social foundation and pushed the boundaries of the ecological ceiling (Raworth, 2018). Due to a heavy focus on profit, the planet and its people have been forgotten. However, there is an opportunity to reverse the damage done by humans and restore the relationship between nature and humankind (Kirwan & Fu, 2020). This paper will explore one of these opportunities to restore balance between the environment and humankind.

The opportunity addressed in this paper is the use of technology. In the past few years, technology has hyper-accelerated us towards the fourth industrial revolution (McKinsey & Company, 2022). This revolution can be characterized by disruptive technologies such as artificial intelligence (AI), big data, quantum computing, the Internet of Things (IoT), blockchain, 5G wireless, and digital twins (DTs) (Allam, 2020; Choi et al., 2022; Faisal et al., 2024; Kirwan & Fu, 2020).

As these technologies start to become part of our daily lives, we move to become one with them on both physical and social levels. We implement devices like pacemakers in our bodies to monitor our health and smartphones have become an extension of ourselves.

Kirwan and Fu (2020) write about the convergence between nature, humankind, and technology. According to them, this convergence is taking us to the next stage of evolution. Cities are the most notable places where these three come together. As more than 50% of the global population lives in cities, this is the place where balance is needed most (The World Bank, 2023). The presence of nature in these cities is crucial to providing clean air, facilitating water drainage, and creating a healthy living environment for the people living there (WUR, 2024). This is why it is crucial to explore the opportunities that bring harmony between nature, technology, and humankind, promoting a balanced and sustainable coexistence.

The United Nations (UN) has taken note of the current state of the planet and has set Sustainable Development Goals to guide the world towards becoming more sustainable. One of these SDGs is to make cities and human settlements inclusive, safe, resilient, and sustainable (United Nations, 2015). With this, they have set a clear objective for the world. In Kirwan and Fu (2020) the authors propose the question: "How can we design and operate our cities to keep balance in nature, ensure the well-being of humankind, and optimize the use of our technology? How can we make our cities smart?"

1.1 Smart Cities

The Smart City is a popular concept in cities around the world to get to a new level of technological innovation and quality of life (Kirwan & Fu, 2020). Anthopoulos (2017) describes a smart city as: “An urban space that is surrounded by or is embedded with ‘smart systems’ or a city with ideas and people that provide clever insights”.

In contemporary society, cities are increasingly trying to incorporate technology to become smarter. Kirwan and Fu (2020) argue that adding technology like IoT does not automatically make a city smart. Anthopoulos (2017) argues that smart systems should encompass not only technology, but also the collective intelligence of their people and organizations. In the same work, the following definition is given for the smartness of a city: “The ‘smartness’ of a city describes its ability to bring together all its resources, to effectively and seamlessly achieve the goals and fulfill the purposes it has set itself” (Anthopoulos, 2017; ISO, 2014).

In a report from ISO[1] (2014) the city is called a system of systems. It is stated that for the city to succeed, all key stakeholders need to come together and combine their efforts and resources to overcome the challenges and use the opportunities that the city faces.

1.2 The City as a Living Organism

In their book, Kirwan and Fu (2020) draw a comparison between the city and a living organism. Just like an organism, the city consists of multiple functions working together as a system. They write that there are three key concepts for seeing the city as a living organism.

The first concept is to view nature's systems as dynamic, self-regulating systems. Cities need to regulate operations in real-time, responding to all city functions at the same time in harmony. This harmony or balance is also referred to as “Homeostasis”. Homeostasis is defined as a self-regulating process by which a living organism maintains internal stability while adjusting to changing external conditions (Mas-Bargues et al., 2023). This term is most commonly used in physiology to describe the systems that ensure balance in an organism. For instance, the way the human body regulates its temperature is around 37°C (Frontiers, n.d.). Here the body maintains its temperature by sweating when there is too much heat, and by shivering when it gets too cold. Just like a living organism, the city needs to constantly adjust to internal and external conditions. For example, excess emissions from increased traffic can negatively impact the city’s environment, which also impacts the well-being of the citizens, causing an imbalance in the ecosystem. Kirwan and Fu (2020), write that homeostasis can be achieved in human systems by governments with an open policy that allows for a continuous stream of innovative ideas to advance and enhance the system. As the city develops, more functions within it will have the capacity to self-regulate. Currently, you can think of traffic systems that have become increasingly self-regulating based on a constant flow of real-time information. Kirwan and Fu (2020) define a self-regulated city as one that can manage and adapt its operations in real-time based on

[1] International Organization for Standardization

data and simulations. By building self-regulating systems, we can ensure urban homeostasis (Kirwan & Fu, 2020).

The second concept is to incorporate the design and functions of systems as a form of biomimicry. Biomimicry is the concept of imitating patterns and flows of nature in the design process to solve human problems (Benyus, 1997). An example of biomimicry is the way photosynthesis in plants is observed to create massive solar arrays to efficiently harness solar power (Fig. 1) (Kirwan & Fu, 2020). Another example is, how the passive cooling systems of termite hills are used in the design of high-rise buildings to create natural ventilation (Biomimicry Institute, 2022).

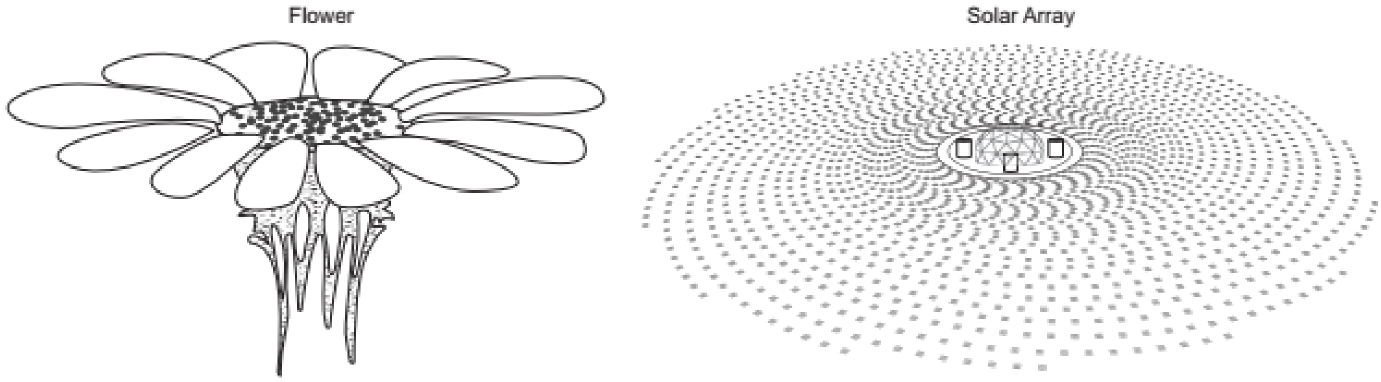

Figure 1 - Biomimetic models. Adopted from (Kirwan & Fu, 2020)

The third concept is to look at the city as a metaphorical body with all its functions in the broadest sense. Just like a human, the city has functions for the brain (Control center), blood system (Flow of information), immune system (Security), muscular system (Mobility), and digestive system (Waste Management) (Kirwan & Fu, 2020). In both humans and cities, systems work together to respond to internal and external conditions. Next to these systems the thing cities share with living organisms is DNA. Every city has its own unique history, culture, and preset assets. There are no two cities the same. According to Kirwan and Fu (2020), a city needs to have a fundamental understanding of its unique aspects, its advantages, and its disadvantages. This city's DNA must be incorporated into the strategies of the city for it to succeed. Using these three concepts from Kirwan and Fu (2020) this paper will treat the city as a living organism that needs its systems to be in balance for it to prosper.

1.3 Collective Intelligence

Within the uniqueness of each city lies its collective intelligence, Kirwan and Fu (2020) describe it as “the positive emergence of group-wisdom from crowdsourcing intellectual capital.” Collective intelligence is a mix of knowledge/information, software/hardware, and technical experts. This comes from the view that a city’s whole being is greater than the sum of its parts. Like in nature, where a single ant or bee does not have the skills to manage the whole colony, the collective can sustain the colony for generations (Kumar et al., 2022). Looking at the city with a holistic approach will allow for a better model or simulation of the city in which technology is dedicated to optimizing the city's systems and the well-being of the citizens (Kirwan & Fu, 2020). Kirwan and Fu (2020) assert that collective intelligence maintains homeostasis and facilitates seamless collaboration among all systems. They write that combining collective intelligence and AI will allow cities to become self-regulating through sensors, data analytics, and real-time processing of city operations. However, they mention that the major challenge so far is to link all the city's systems together into an operating system that can create a holistic view of the city and its systems.

1.4 City Operating System

The operating system mentioned above sounds very familiar to the Urban Digital Twin (UDT). Raes, Michiels, et al. (2022) and Jedoub et al. (2023) describe a UDT as a living digital representation of the city's existing objects, infrastructure, systems, and processes. This representation has a real-time bi-directional flow of data from and to the real world. Moreover, the UDT can be used to monitor, manage, and optimize city systems. Cities have been implementing different types of UDTs. For instance, in the Netherlands alone 37.5% of municipalities with over 100.000 citizens are working on UDT projects (Ávila Eça De Matos et al., 2022). Most of these initiatives focus on single-city systems, like traffic or city planning.

1.5 Research Question and Research Objective

In a time where there is a severe imbalance between nature and humankind, cities guided by the UN SDGs are ambitiously embarking on digital transformation journeys to restore balance (Joint SDG Fund, 2023). Many of these digital transformations include the use of UDTs (Jedoub et al., 2023). This allows cities to monitor, manage, and optimize their operations. However, while many of these initiatives show promise within individual systems, they don't look at the city as a whole. When looking at the city as a living organism it becomes clear that it is a complex, interconnected network of systems and needs to be treated like one. Here it is important to understand that changes within one system can influence others in both positive and negative ways. Applying a holistic approach and linking these systems together in a system could enable self-regulation within the city. Having a system that can help manage and adapt the city's operations in real-time based on data and simulations could bring a city closer to homeostasis. However, as noted by Kirwan and Fu (2020), it has been a major challenge to link all the systems inside a city together in one place. This paper tackles this challenge by adopting a holistic approach to developing a UDT design that interconnects the whole city ecosystem in one place. Through this, the paper will explore how UDT technology can enable the self-regulation of a city. It should be noted that this is an explorative research into the holistic approach of a UDT. This study will not be a comparative study to see if the holistic approach is better or worse than a fragmented approach. This paper contributes both to academic literature and to the development of cities. First, to the academic literature by introducing a holistic approach to UDT design and by laying the groundwork for further research into UDTs. Second, it contributes to cities by providing a high-level design for a system that can help the city enable self-regulation and move towards urban homeostasis.

To assess the potential of a holistic approach to urban digital twin design, the following main research question has been defined:

How does a holistic approach to urban digital twin design enable the self-regulation of a smart city?

To answer this main research question the following sub-research questions have been formulated:

1. What is self-regulation in a smart city?
2. What is an urban digital twin?
3. What is a holistic approach to urban digital twin design?
4. What are the main components of a holistic urban digital twin design?

1.6 Thesis Structure

This paper begins by introducing the topic and providing the context for the research (Fig.2). It will also discuss the study's focus and scope, as well as its relevance and the research questions to be addressed. The second chapter will cover the literature review and conceptual model. This chapter will be the academic backbone of the study. Chapter 3 will discuss the research methodology. Chapter 4 will concentrate on the meta-architecture of the holistic urban digital twin design, providing a clear understanding of the UDT. The next chapter will go into the two main components of the design ecosystem-driven and self-regulation. In Chapter 6 the results and findings are discussed. This leads to the final chapter where the conclusions, implications, limitations, and directions for future research will be discussed. Finally, in chapters 8 and 9 the references and appendices can be found.

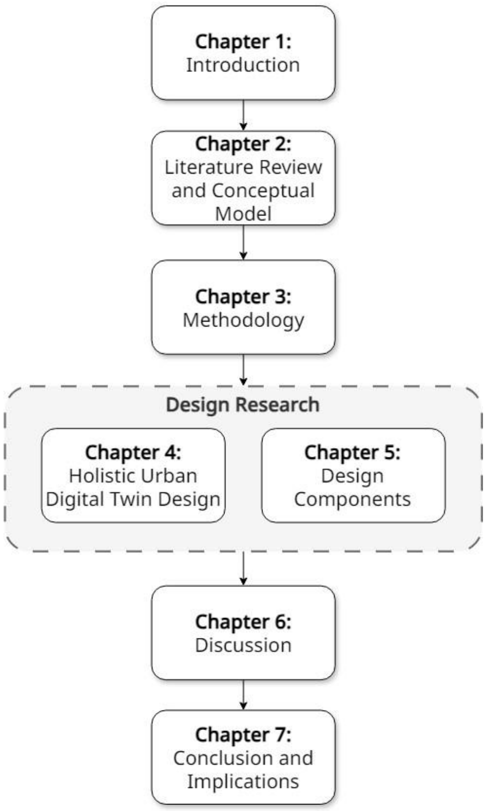

Figure 2 - Thesis Structure.

2 Literature Review and Conceptual Model

2.1 Smart Cities

Anthopoulos (2017) traces the evolution of smart cities back to the late 1990s, when Graham and Aurigi (1997) used terms like web or virtual city to describe information technology network initiatives that aimed to create online communities. Most of these communities were created to provide public information for city authorities (Anthopoulos, 2017). Graham and Aurgi (1997) also introduced the term "Digital City" which was related to initiatives that focused on citizen participation. Anthopoulos (2017) also talks about the first digital city in practice, which was Amsterdam in 1994. This project was the result of activists who wanted to enable dialogue between the community and the municipality. When considering the evolution of smart cities, most were created to use IT to increase democracy in their communities. This can be linked to the idea of citizen participation and collective intelligence as described by Kirwan & Fu (2020). Over time, the concept of a smart city became synonymous with embedding technology into the city. Now the smartness of a city refers to how it can bring together all of its resources to achieve its goals (Anthopoulos, 2017; ISO, 2014).

This paper will use seven defined principal objectives to create a clear understanding of what a smart city is (Tbl. 1) (CAICT & EUCPDSFII, 2016). These objectives describe the vision of what a smart city should be. In this vision they emphasize the importance of utilizing information technology, creating a sense of sharing, transparency, equality, social participation, innovation, and openness. These objectives were used as they are the result of research on both European and Asian smart cities, making them more generalizable.

- To achieve a unification and smart application to information infrastructure and public infrastructure (e.g., the management of green resources, dynamic monitoring of the environment, and the classification of wastes)
- To create a sense of sharing for environmental protection and a low-carbon lifestyle
- To establish a transparent, fair, and inclusive mechanism of incentives
- To achieve equal access to basic public services, as well as a universal sharing of knowledge and information
- To drive forward the modernization of both the system and the capability to govern the city, with greater and fuller social participation

- To cultivate plurality and innovation in business models
- To open up the data of public sectors, to bring down barriers and limits between departments, and to ensure the entitlements of all stakeholders

Table 1 - Principle Objectives of Smart Cities. Adopted from (CAICT & EUCPDSFII, 2016)

2.1.1 Smart City Dimensions and Domains

In the last two decades, there have been a plethora of different ways to conceptualize the world around us (Appx. I). While triple helix models like people-planet-profit, and social-environmental-economic help us grasp the different parts of reality we live in, it becomes increasingly difficult to separate one from the other because of their convergence with each other. For this paper, the dimensions described in Kirwan & Fu (2020) will be used to define the different dimensions of a city. These are the 'Physical Domain', the ' Human Realm', and the 'Technology Sphere'. Through these dimensions, three clear goals have been set; the well-being of humankind, the balance in nature, and the optimization of technology. To show how the three come together within the city Kirwan and Fu (2020) present six layers that make up the city dimensions (Fig. 3). These six layers and three dimensions represent the city ecosystem.

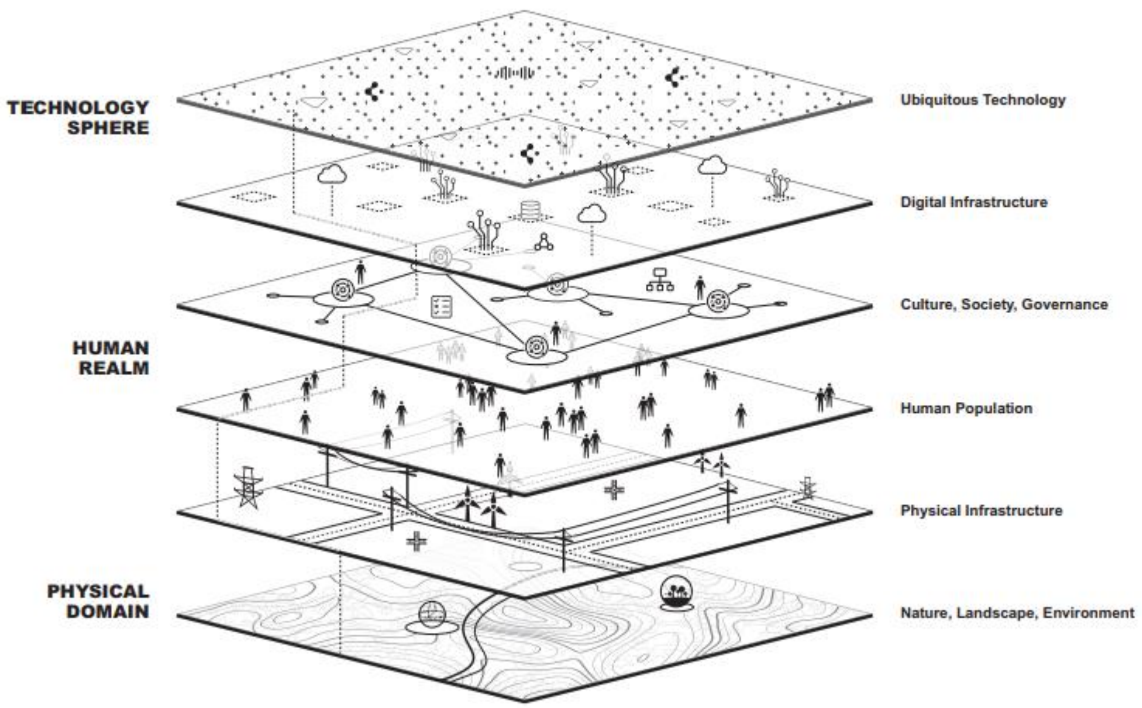

Figure 3 - City Dimensions. Adopted from (Kirwan & Fu, 2020)

Within academic smart-city literature, a multitude of different city domains are mentioned. Anthopolous et al. (2016) created a comprehensive overview of these different domains. It was then split into six domains smart governance, smart people, smart mobility, smart living, smart environment, and smart economy (Anthopolous et al., 2016; Giffinger et al., 2007). These six domains contribute to the overall vision of a smart city. In each domain, technology is used to enhance different aspects of urban life. An extended description of these can be found in Appendix II.

Lee and colleagues (2014) provide key pointers on the process of building a smart and sustainable city. They emphasize the need for a movement towards interactive services to engage citizens, the need for a strategic balance between data transparency and privacy to boost innovation, and the use of advanced technology to support new value for cities. To add to this Dai et al. (2024) created a framework that describes an iterative cycle of five stages for smart city transformation. These five stages include goal definition, technology innovation, strategy development, plan implementation, and evaluation. Dai et al. (2024) emphasize the need for interaction between stakeholders and note that transformation involves constant reiteration.

2.1.2 Self-Regulating Smart Cities

As described in the introduction, self-regulating systems aim to maintain a living organism's homeostasis while adjusting to changing internal and external conditions (Kirwan & Fu, 2020). When applying the concept of Kirwan & Fu (2020) and considering the city as a living organism, the self-regulation of a city refers to the ability of a city to manage and adapt its operations in real-time based on data and simulations. This means that a city that is not able to manage and adapt its operations in real-time is not self-regulated under this paper's definition. Just like living organisms, cities are systems that require external resources, energy, and nutrients to maintain homeostasis (Kirwan & Fu, 2020). To achieve self-regulation the use of technologies like AI could be used to create a system with evolutionary logic. Researchers like Laurençon et al. (2024) are currently working on 'Homeostatic Regulated Reinforced Learning' frameworks. Which are AI algorithms that have evolutionary logic built into them. Their goal is to develop models that can simulate a real-world biological agent's homeostatic mechanism, which means they want to recreate the way biological organisms achieve homeostasis. However, while these models are still in early development, other technologies can enable the city to become self-regulating. One of these technologies that can enable the city to become self-regulating is the digital twin technology, which will be the main technology discussed in this paper. Incorporating self-regulating components in the design of a city-wide system would help cities efficiently manage their resources, reduce risks, and adapt to changing conditions in real-time (Kirwan & Fu, 2020).

2.2 Digital Twins

The concept of digital twins (DTs) has been around since 2002 when Micheal Grieves first presented the idea as part of product lifecycle management (Grieves, 2002, 2019). Grieves and Vickers (2016) write that up until that point, the only way to get extensive information on a physical object would be to get up close and observe it. A DT fixes that by providing a virtual representation of the physical object containing the wanted information (Jones et al., 2020; Grieves & Vickers, 2016). DTs can be characterized by a seamless integration of the physical and digital realms (Tao et al., 2019). Jones et al. (2020) write that there are three main components of a DT, a physical object, a virtual representation of that object, and a bi-directional flow of data that feeds data from and to the object. A clear definition of a DT is a common challenge with the concept. To be able to have a clear definition of a DT Kritinger et al. (2018) distinguish models based on the level of data integration between physical and digital objects (Fig. 4). Where a digital model is only a digital representation of a physical object with manual data flows between the objects, digital shadows only have an automatic data flow from the physical object to the model but not vice versa, and the DT has an automatic data flow from and to the object and model. This paper will use the definition of Kritzinger et al. (2018) when mentioning DTs.

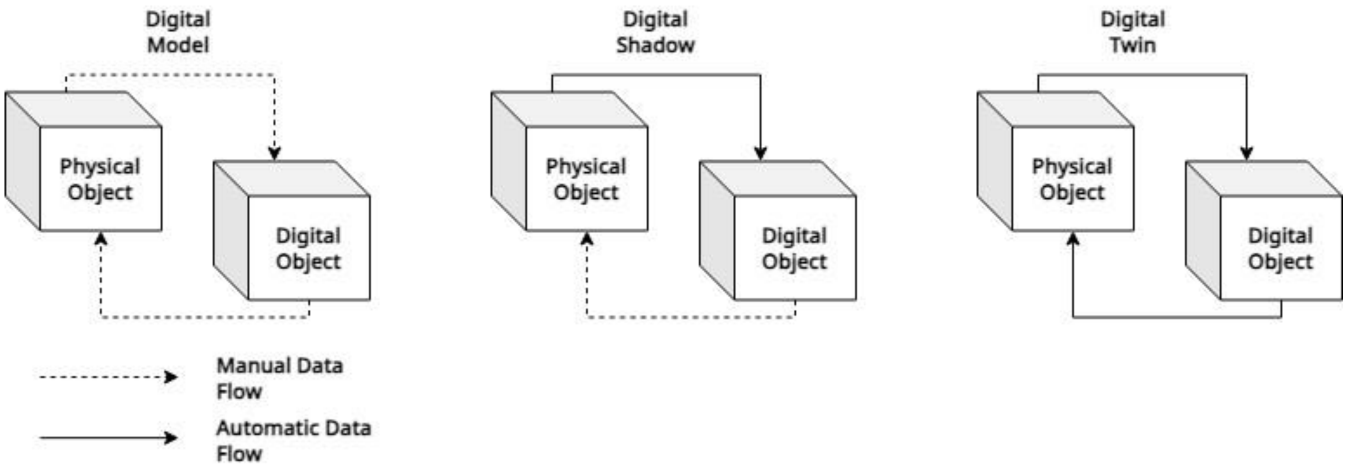

Figure 4 - Digital Twin Concept. Adopted from (Kritzinger et al., 2018)

Verdouw et al. (2021) present six different types of DTs, namely the imaginary, monitoring, predictive, prescriptive, autonomous, and recollection DTs.

Imaginary DTs represent the state and simulate the behavior of reference objects that do not yet exist in the real world (Verdouw et al., 2021). These are used to simulate how not-yet-existing objects would affect the real world inside the virtual world. Consider simulating the effects of a new solar panel to see how much sunlight it would capture when placed on a building.

Monitoring DTs represents the current and historical state and behavior of objects that exist in the real world (Verdouw et al., 2021). These DTs are mostly used to monitor the current state of objects.

Predictive DTs project the future state and behavior of real-life objects (Verdouw et al., 2021). It uses prediction models to show what real-life objects will look like in the future. Think of predictive maintenance.

Prescriptive DTs represent the effects of interventions in a present model on a future model (Verdouw et al., 2021). Here models simulate different interventions that can correct possible issues detected by monitoring DTs or in future forecasting by predictive DTs. Here the decision for intervention in the real world is still made by a human.

Autonomous DTs go a step further than prescriptive DTs, executing interventions autonomously and fully controlling the behavior of a real-life object without human intervention. Here the loop can be closed, and the DT can also be self-learning so it adapts to changes in the system (Verdouw et al., 2021).

Recollection DTs represent the past state and behavior of objects that no longer exist in the real world (Verdouw et al., 2021). These differ from imaginary DTs because they accurately depict historical objects.

2.2.1 Applications in Different Industries

Various industries, including manufacturing, agriculture, and healthcare, have adopted DT technology in the previous 20 years (Kritzinger et al., 2018; Machado & Berssaneti, 2023; Purcell & Neubauer, 2023). In this section, these applications will be discussed.

Manufacturing

Out of all the different industries DTs are used in the most advanced, which is manufacturing. DTs are implemented at all levels of manufacturing, including at the unit level (Böttjer et al., 2023). Kritzinger et al. (2018) found that a manufacturing DT offers the opportunity to simulate and optimize the best production system including logistics. In manufacturing the main goal of using DTs is to increase productivity and efficiency in production, planning and control, maintenance, and layout planning (Kritzinger et al., 2018). Rosen et al. (2015) highlight the importance of autonomy and DTs for the future of the manufacturing industry. They mention how DTs enable autonomous systems by providing them with accurate models of the current process state and their behavior. This helps autonomous systems make informed decisions and function efficiently within the manufacturing process. Additionally, D'Amico et al. (2023) highlighted that the main challenges of DTs in manufacturing are interoperability, complexity, and security concerns. To mitigate some of these challenges, they advocate for a system of systems approach to create a network of connected DTs that can enhance each other. DTs in the manufacturing industry have the potential to reduce costs, increase quality, and improve efficiency (Attaran & Çelik, 2023).

Agriculture

Currently, in the agricultural sector, DTs are beginning to show their potential by helping overcome limitations in decision-making and automation (Purcell & Neubauer, 2023). In their paper, Purcell and Neubauer (2023) highlight the different use cases of DTs in the sector. These use cases include crop monitoring, resource optimization and cultivation support, livestock management, monitoring, and optimization, as well as controlled urban aquaponic farming. Verdouw et al. (2021) underscore the potential of DTs to enhance farming productivity and sustainability to unprecedented heights. By incorporating DTs into farm management, physical workflows can be separated from planning and control, allowing farmers to manage their farms remotely using real-time data.

Healthcare

DTs are used in almost every aspect of the healthcare sector. From precision healthcare where they are used to diagnose and identify treatments to hospital management where they are used as a simulation tool to optimize resource allocation (Ghatti et al., 2023). Machado and Berssaneti (2023) suggest that DTs in healthcare may be transitioning out of their initial phase and getting increasingly mature due to the knowledge drawn from the manufacturing sector. Moingeon et al. (2023) show another usage of DTs in healthcare, they see the technology being used to simulate the efficacy and safety of drugs or medical devices. The DTs make it possible to perform virtual experiments that would be too risky to conduct on human patients. Cellina et al. (2023) describe the use of digital human twins, where patients are simulated to monitor disease progression and optimize treatment plans. Going back to what was discussed above, considering the city a living organism and comparing its systems to those of a human body, a great deal can be learned from the applications of DTs in the healthcare sector.

2.2.2 Benefits and Challenges

Digital Twin Technology offers many different benefits across different sectors. Its main advantages include improved productivity, efficiency, and decision-making (Kritzinger et al., 2018; Purcell & Neubauer,2023; Rosen et al., 2015). Next to this DTs also facilitate resource optimization, remote management, and simulations (Cellina et al., 2023; Ghatti et al., 2023; Moingeon et al., 2023; Purcell & Neubauer,2023; Verdouw et al., 2021).

From the literature, it is also evident that the use of DTs has some challenges. Most of the papers discussing DTs mention challenges with interoperability, complexity, data quality, privacy and security, ethical considerations, and the need for a clear definition (Cellina et al., 2023; Ghatti et al., 2023; Purcell & Neubauer, 2023; Verdouw et al., 2021). Böttjer et al. (2023) also mention the challenge of developing robust data acquisition and processing techniques that ensure the veracity of the data going into the DTs.

While DTs present immense potential for enhancing efficiency and decision-making across sectors, it's crucial to acknowledge that they do have their challenges. Overcoming these challenges is vital for optimizing the benefits of this technology. This paper looks to contribute to solving these challenges through a holistic approach to the design of UDTs.

2.2.3 Urban Digital Twins

While DTs in other industries have been around for some time now, Urban Digital Twins started to gain interest from 2016 onward (Jedoub et al., 2023; Lei et al., 2023). Whereas

DTs in sectors like manufacturing and agriculture are mostly made with production chains and machines in mind, DTs in healthcare and cities have more human factors to consider (Lehtola et al., 2022). As the city is a complex interconnected network of systems and domains that constantly change, it is difficult to manage and predict (Lei et al., 2023). Currently, there are a plethora of different applications for UDTs to fulfill. Yang and Kim (2021) identified and classified the different UDT applications into six categories (Tbl. 2). These categories are supported by the findings of both Ávila Eça de Matos et al. (2022) and Jedoub et al. (2023).

Application	Description
Urban Planning and Design	Digital Twins that are used to simulate the impact of urban development changes, such as housing, landscape, and noise management.
City Management and Operations	Digital Twins aid in managing infrastructure like water and sewage systems, as well as waste management.
Transportation	Digital Twins that simulate the effects of new infrastructure on traffic, public transport, and emergency response plans.
Environment and Energy	Digital Twins that simulate climate events, wind paths, and predict solar power generation.
Disaster Management	Digital Twins that are used to simulate natural disasters and contagious diseases to prepare emergency responses.
Other Applications	This includes smaller applications like guiding tourism and enabling sharing economy platforms.

Table 2 - Current Urban Digital Twin Applications. Adopted from (Yang & Kim, 2021)

Lei et al. (2023) created a DT lifecycle to better understand UDTs (Fig. 5). Six phases comprise the lifecycle: (1) collecting, (2) processing, (3) generating, (4) managing, (5) simulating, and (6) updating. The initial phase involves the collection of a large volume of heterogeneous data from various sources such as the IoT, Lidar, and other existing data sources. In the second phase, this data is converted and integrated into the system. Subsequently, the third phase utilizes the data to create a virtual object. In the fourth phase, the DT's quality and data are managed. Next in the fifth phase, the DT is used to simulate different urban what-if scenarios. And finally, in phase six, the DT sends the changes back to the physical world. Lei et al. (2023) note that the lifecycle of a DT can be very dynamic in a city and to be effective it needs to be able to handle a large volume of heterogeneous data.

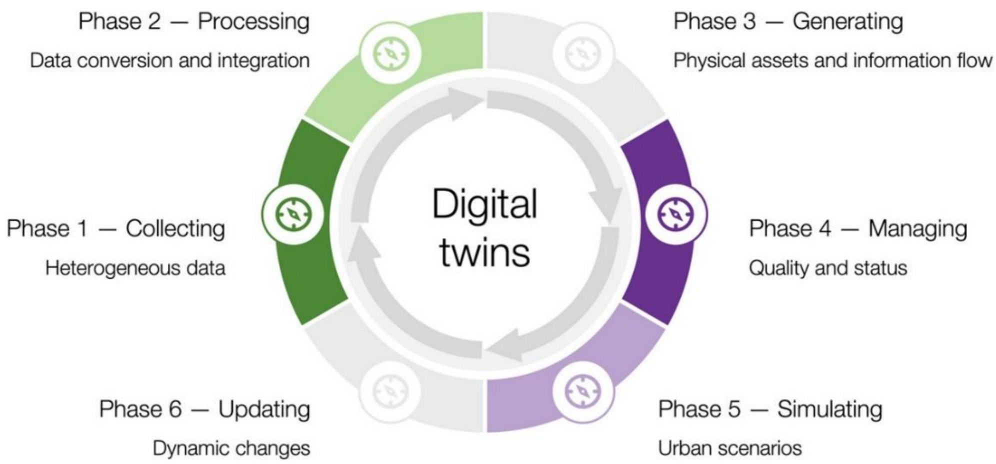

Figure 5 - The Lifecycle of Digital Twins in Urban Domains. Adopted from (Lei et al., 2023)

The Digital Urban European Twin (DUET) initiative is spearheading the development of UDTs. Raes, Michiels, et al. (2022) demonstrate their ongoing pilot projects in Athens, Pilsen, and Flanders. Their UDTs are intended to assist cities in traffic enhancement, environmental conservation, and population well-being. In their UDT they combine three models to simulate traffic, air quality, and noise levels.

The traffic model utilizes a variety of data sources to measure the impact of diverse what-if scenarios, such as the introduction of new developments and the closure of lanes. In terms of air quality, the models simulate the dispersal of air pollution and its effects on the atmosphere. To achieve this, the model uses data like traffic volume and wind speed to calculate how much pollution is being dispersed. Next to this, noise emission models measure the noise generated by industrial activities and traffic to generate noise maps and compute the noise exposure to the city's population.

By connecting these three models they can run simulations of complex what-if scenarios, such as the impact of noise levels and air quality if the city changes the speed limit on a specific street. The goal of these simulations is to assist in the design, implementation, and evaluation of new policy measures aimed at protecting the environment and the population from negative impacts. DUETs, as described in Raes, Michiels, et al. (2022), are one of the better examples that show the potential of combining models from different domains to assist in achieving the United Nations Sustainable Development Goals.

Similar to other industries, a variety of technical and non-technical challenges are hindering the adoption of UDTs (Lei et al., 2023). The most significant technical challenges identified include interoperability, system integration, finding skilled manpower, and system architecture. The major non-technical challenges are mostly related to there not being a clear understanding of the business model, purpose, ownership, and permissions. Weil et al. (2023) echo these challenges and add data acquisition, data quality, infrastructure, human and capital resources, and harmonization between models. Looking at these challenges, it is noticeable that most of them arise from a lack of understanding of the application of a UDT.

To summarize, digital twins in cities look very promising but still struggle with some challenges that need to be addressed. Many of the current applications of UDTs are only focused on a single system within the city without considering the city as a whole rather than the sum of its parts. Weil et al. (2023) suggest in their future research section, to investigate a holistic approach to UDTs. This paper will listen to this suggestion to research a holistic approach to UDTs, as a holistic approach could address some of the main challenges UDTs have. This paper will also take on the main non-technical challenge of there not being a clear understanding of what a UDT is.

2.3 Holistic Urban Digital Twin Design

As described in previous sections, the city is a complex interconnected network of systems that can be considered a living organism. Understanding that the systems in a city are not isolated but have an impact on each other is very important. For instance, when changes occur in the environment this can directly affect the health of the city's population (Remoundou & Koundouri, 2009). Another example from Raes, Michiels, et al. (2022) is how an increase in traffic can increase air and noise pollution, which impacts the environment and the citizens' well-being. However, most current UDT applications tend to focus on individual systems such as urban planning, the environment, or mobility without incorporating the effects other systems can have (Ávila Eça De Matos et al., 2022; Jedoub et al., 2023; Yang and Kim, 2021). This fragmented approach can be effective for individual systems but lacks a comprehensive understanding of the whole city ecosystem. This could lead to limitations in the city's ability to make informed decisions on a holistic level (Bécue et al., 2020).

Considering the city as a living organism and as a whole rather than the sum of its parts allows for a more interconnected view of its systems (Kirwan & Fu, 2020). Interconnecting the systems of a city in one UDT could lead to a more accurate representation of the entire city (Bécue et al., 2020). Looking at the healthcare sector, where digital human twins are simulating the whole patient to monitor for disease progression and optimize treatment plans (Cellina et al., 2023). In the city, one could see the whole city as the patient, where health and well-being are monitored and treatment plans are simulated to make the city healthy and in balance. Raes, Michiels, et al. (2022) already showed that combining different models of the city can enhance the performance of what-if scenario simulations. Applying this to the whole city could offer a complete and interconnected view of the city (Shahat et al., 2021). This interconnected view would enable urban planners, designers, and the public to collaborate effectively to make more informed decisions to create a smart and sustainable city (Dembski et al, 2020).

To develop a holistic urban digital twin, an initial design is crucial. Given the novelty and complexity of this UDT, stakeholders need a clear understanding of what the system is. This is where meta-architecture can help all stakeholders communicate the holistic UDT idea. Meta-architecture creates a shared vision of the system containing the context, goals, scope, and architecture strategy of the system, and sets guidelines for the components in the design. This paper suggests that the design of a holistic UDT is comprised of the meta-architecture and at least two main components that are central to the design: 'Ecosystem Driven' and 'Self-regulation'. These components and their sub-components will be addressed further in the sections below. The first proposition is as follows:

Proposition 1: *The design of a holistic digital twin is comprised of meta-architecture, ecosystem-driven, and self-regulation components.*

Meta-Architecture

Given the novelty and complexity of a holistic UDT, a clear understanding needs to be created so it can be communicated to all stakeholders. Meta-architecture can assist in creating this understanding. In meta-architecture, a set of high-level decisions, principles, and criteria are defined to ensure the functionality of a system as intended (Anthopoulos, 2017; Kirwan & Fu, 2020; Malan & Bredemeyer, 2005b). The meta-architecture strongly influences the structure of a system but is not the system itself (Malan & Bredemeyer, 2005b). It guides system architects by establishing the **architectural strategy**, including principles, philosophy statements, metaphors, and organizing concepts that will guide the design of the architecture (Malan & Bredemeyrer, 2005a). Additionally, it guides non-technical stakeholders by creating an understanding of the **context**, **scope**, and **goals** of the system.

Malan and Bredemeyer (2005a) developed a guide for developing meta-architecture. The following guide consists of three main activities.

The first activity is to understand the context and goals, as well as set a scope. At the start, it is important to gather enough input to make a quick initial version of the meta-architecture, which can then be evaluated and built upon. The most important first step is to set the scope and to do this, a clear understanding of the system's context and goals is needed. To understand a context, a shared vision must be built. In this phase, questions like "What are the use cases?" and "What is the context of the system related to others?" need to be answered. In this section, creating a conceptual domain model is recommended by Malan and Rademeyer (2005a). Additionally, all stakeholders and their goals need to be identified.

The second activity is to set the architectural strategy. To guide architects, architectural objectives and principles are defined. This can be achieved by deciding what capabilities need to be built in order to achieve the system's set goals. Following this, an architectural pattern needs to be selected. An architectural pattern defines the vocabulary of the components and connectors, with constraints on how they can be combined (Shaw &

Garlan, 1996). When the architectural strategy is clear, everything must be documented. Malan & Bredemeyer (2005a) describe architecture as being created by the few for the many's consumption. Documentation is a tool for communication with stakeholders. Especially the reasoning behind the decisions needs to be recorded, as these provide traceability.

The third and final activity is to validate the meta-architecture. The main objective of validation is to get input and feedback from stakeholders. As revisions are made, the meta-architecture should provide a clear understanding of the proposed system.

According to Malan and Bredemeyer (2005a), the possible outcomes of the meta-architecture include strong sponsorship and alignment with stakeholders. Although Malan & Bredemeyer (2005a) mainly discuss meta-architecture from within the business context, the principles can also be applied to the public sector as they can create a clear understanding of any system. This paper will create a meta-architecture of the proposed system by discussing the context, goals, scope, and architectural strategy. Moreover, this paper proposes that this meta-architecture sets the guidelines for the components in the design. This leads to the formulation of the second proposition:

Proposition 2: *The meta-architecture sets guidelines for the components of a holistic urban digital twin design.*

Ecosystem Driven

One important component of the holistic UDT design is knowing who can use and control the system. As mentioned in previous sections the main objective of a smart city is to use technology to create a sense of sharing, transparency, equality, social participation, innovation, and openness (CAICT & EUCPDSFII, 2016). To achieve this the holistic UDT needs to be ecosystem driven. Kirwan and Fu (2020) believe that an open-source approach to the system would allow for greater flexibility and adaptability to the city's ever-changing environment. The holistic UDT should be **open to all citizens** to engage them and gather valuable feedback on key urban planning and policy decisions, thereby incorporating their needs into the city's management and operations (Kirwan & Fu, 2020; White et al., 2021). The holistic UDT would become a living lab for the city, where its **collective intelligence** comes together.

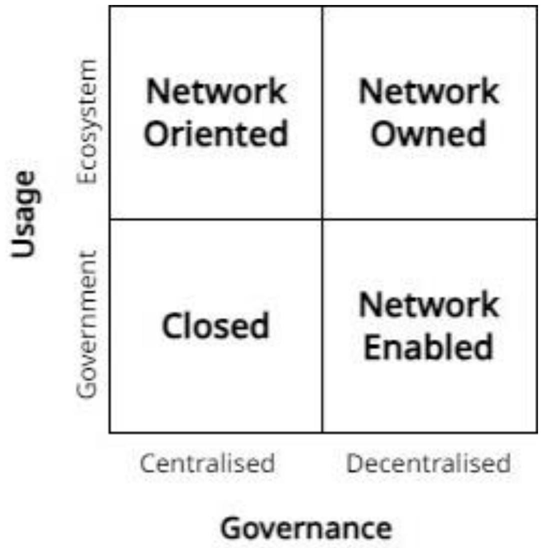

Figure 6 - UDT Business Model Scenarios. Adopted from (D'Hauwers & Kogut, 2021)

To understand the possible business model scenarios for UDTs better, D'Hauwers and Kogut (2021) identified four different models (Fig. 6). These business models are based on whether they are used and controlled by the government or the ecosystem. The ecosystem described here refers to all citizens and organizations in a city. Looking for a holistic solution incorporating a collaborative and open-source approach the model selected would be an "Outside-Out" or "Network Owned" Digital Twin as described by D'Hauwers et al. (2021) and D'Hauwers & Kogut (2021)(Kirwan & Fu, 2020). D'Hauwers and Kogut (2021) elaborate on this form by calling it an initiative **governed by the ecosystem** rather than solely by a city. In this model, the government plays a facilitating role along with industry, science, research, and society. D'Hauwers et al. (2021) describe the purpose of this model as supporting governmental policymaking by incorporating the ecosystem into the decision process. Additionally, it aims to drive co-innovation, which encourages the ecosystem to innovate using the UDTs data. The ecosystem-driven design of the holistic UDT not only supports government policymaking but also provides a platform for private enterprises to invest in capital, technology, and business solutions (Kirwan & Fu, 2020).

Self-Regulation

Looking back at the concept of Kirwan & Fu (2020) and considering the city as a living organism, the self-regulation of a city refers to the ability of a city to manage and adapt its operations in real-time based on data and simulations. This suggests that if a city can manage and adapt its operations in real-time based on data and simulations it can be self-regulating. Moreover, when looking at the definition of a DT from Kritzinger et al. (2018), it is a virtual representation of a physical object with bidirectional synchronization (Fig. 4). This means that both the virtual model and the physical object get updated automatically. This alludes to that DTs have **autonomous** properties and leads to the second main component of the holistic UDT design.

An autonomous system, or one with autonomous properties, is defined as a system capable of self-controlling its behavior (Khan et al., 2020; Mele, 2001). Khan et al. (2020) suggest that for systems to be truly autonomous, they should not only be able to analyze historical data and use supervised decision-making models but also incorporate competitive survival strategies and centralized optimization planning/scheduling (Leng et al., 2018). Although there are various degrees of autonomy in literature, this paper defines an autonomous system as one that can function in uncertainty. A system that can learn about its environment, self-diagnose its needs, and adapt to user preferences (Khan et al., 2020; Verdouw et al., 2021).

To accurately represent the physical object and run precise simulations, the DT requires a massive amount of heterogeneous real-time data (Lei et al., 2023). Some of this **data can be acquired** from sensor systems like satellites, UAV imagery, LiDAR, and other IoT sensors within the city (Lehtola et al., 2022). This paper suggests that, based on the ideas of Kirwan & Fu (2020) collective intelligence should also be used as a data source to better incorporate the needs and desires of society into the system. This would mean that the system would have to handle both structured and unstructured data. To handle this large amount of heterogeneous data, AI is needed. Artificial intelligence is essential for effectively managing and interpreting massive real-time data sets (Vaishya et al., 2020; Whang et al., 2023). It is one of the DT ecosystem's core technologies (Lv & Xie, 2022). Raes, Michiels, et al. (2022) argue that a true DT incorporates AI components, enhancing decision-making processes and enabling the system to make better decisions independently.

Developing a holistic UDT as an autonomous system capable of self-diagnosis and adaptable to the needs of the city would enable the city to become self-regulating and move towards urban homeostasis. The United for Smart Sustainable Cities (U4SSC)—a UN initiative coordinated by the ITU[2], UNECE[3], and UN-Habitat[4]—created key performance indicators (KPIs) that can guide the system with its self-diagnosis. U4SSC has established over 80 KPIs to measure a city's progress toward being smart and sustainable (U4SSC, 2017). These KPIs are split into three primary dimensions: economy, society & culture, and environment which are comparative to people, planet, and prosperity and include most smart city dimensions, as mentioned in Section 2.1.1. The full list of KPIs is included in Appendix III.

Using these KPIs, the holistic UDT could self-diagnose and identify areas for improvement. Using the KPIs as metrics for progress could enable the city to progress toward self-regulation. By using data collected from all the city's dimensions it could accurately simulate what-if scenarios to see what optimal solutions to problems could be. It could

[2] International Telecommunication Union
[3] United Nations Economic Commission for Europe
[4] United Nations Human Settlements Programme

eventually evolve from autonomously managing traffic systems and energy grids to making real-time operational or policy decisions (DUET, n.d.). By building a **self-regulating system** within the city that autonomously looks to find a balance between society and culture, the environment, and the economy, urban homeostasis could be ensured (Kirwan & Fu, 2020). This leads to the final proposition:

Proposition 3: *The design of a holistic UDT influences the capability of a UDT to enable a city to achieve self-regulation.*

2.4 Conceptual Model

The following conceptual model (Fig. 7) is based on the combination of smart city and digital twin literature. The model applies the ideas of Kirwan and Fu (2020) for a holistic city operating system to enable self-regulation within cities and leverages the academic literature on UDTs as the technology to make this possible. The model also shows where the propositions lie (Tbl. 3).

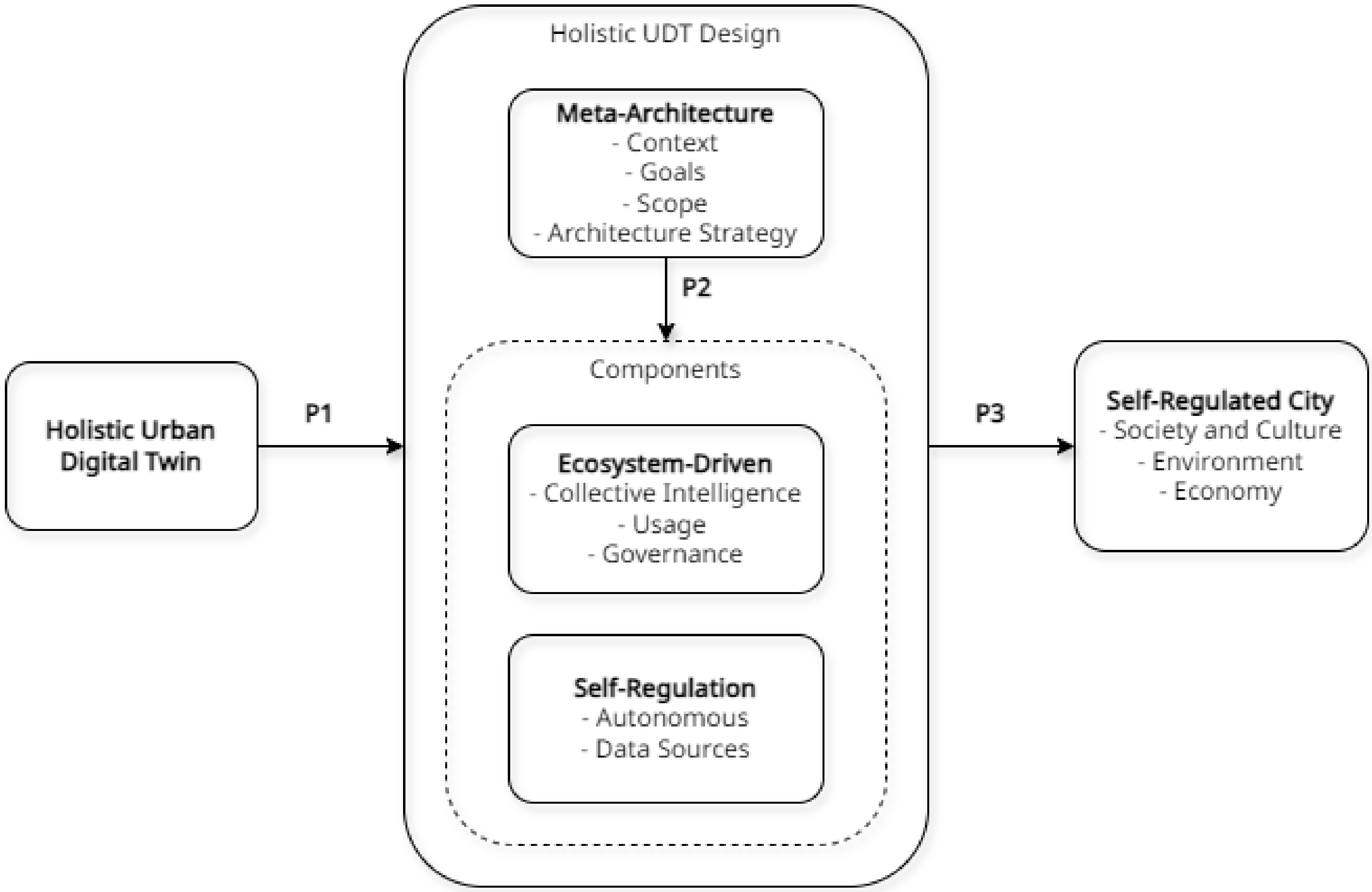

Figure 7 - Conceptual Model

Proposition 1	The design of a holistic UDT is comprised of Meta-Architecture, Ecosystem-Driven, and Self-Regulation components.
Proposition 2	The Meta-Architecture sets guidelines for the components of a holistic UDT design.
Proposition 3	The design of a holistic UDT influences the capability of a UDT to enable a city to achieve self-regulation.

Table 3 - Overview of Propositions

This model shows the holistic urban digital twin as the independent variable, the design of the holistic UDT as the mediator variable, and the self-regulated city as the dependent variable. It shows that the design is comprised of a meta-architecture that provides context, goals, scope, and strategy for the two main components of the design, 'Ecosystem Driven' and 'Self-Regulation'. The first refers to the fact that the holistic UDT is open to and governed by the public to include the collective intelligence of the city. The latter refers to the holistic UDTs' ability to use data and AI to facilitate self-regulation within a city. Finally, this model assumes that the design of the holistic UDT will influence a city's self-regulation to find a balance between society and culture, environment, and economy. All of the individual variables are defined in Table 4.

Variable	Definition
Holistic Urban Digital Twin	**The independent variable**: A holistic urban digital twin
The Holistic UDT Design	**The mediator variable**: The holistic approach to urban digital twin design and the artifact for this study
Meta-Architecture	A high-level blueprint of the proposed system for both technical and non-technical stakeholder alignment
Context	Overview of what the proposed system is
Goals	The goals and objectives of the proposed system
Scope	The focus and boundaries of the proposed system
Architecture Strategy	The principles, capabilities, attributes, patterns, and topology of the proposed system
Components	The two main components to be elaborated and designed in this paper
Ecosystem-Driven	The component that shows how the system should be network-owned, so it is both controlled and used by the whole ecosystem

Collective Intelligence	"the positive emergence of group wisdom from crowdsourcing intellectual capital"- (Kirwan & Fu, 2020)
Usage	How and by whom the proposed system should be used
Governance	How the proposed system should be governed
Self-Regulation	The component that shows how the system enables the city to manage and adapt its operations in real-time based on data and simulations
Autonomous	How the proposed system could perform without human interaction
Data Sources	What data sources are needed to feed the proposed system
Self-Regulated City	**The dependent variable**: A city that can manage and adapt its operations in real-time based on data and simulations

Table 4 – Conceptual Model Variable Definitions

3 Methodology

3.1 Research Strategy

The concept of a holistic UDT is still very novel in the academic literature, with most research focused on UDTs that focus on individual systems within the city. Therefore, a high-level design is still absent. Academic literature has provided a starting point for the design, but to complete the design, more research needs to be done. This paper applies a qualitative approach to guide this research. To achieve this, this paper has adopted the Design Science Research (DSR) framework described by Henver et al. (2004) and Brocke et al. (2020) as the research methodology. DSR is a problem-solving paradigm aimed at generating knowledge through the creation of artifacts. Sitepu (2017) successfully applied this methodology to develop a blueprint for the design of a platform ecosystem in international trade. DSR aims to generate knowledge about how things could be designed to achieve a desired set of goals (Brocke et al., 2020). In this paper, the DSR methodology has been used to develop a holistic UDT design aimed at enabling self-regulation in a city to achieve urban homeostasis.

3.2 Design Science Research Framework

As described in Henver et al. (2004), the DSR framework (Fig. 8) is a conceptual framework to help understand, execute, and evaluate DSR. It addresses real-world problems across multiple domains. It typically begins with an analysis of the environment to identify the problem to be solved. It also entails examining the existing knowledge base to determine what knowledge is already available. This knowledge can take the form of theories, frameworks, or design artifacts such as models or methods. If a solution cannot be found, DSR seeks to create one by combining, revising, and extending existing design knowledge. During a DSR study, diverse methods are applied, including interviews and literature reviews (Brocke et al., 2020).

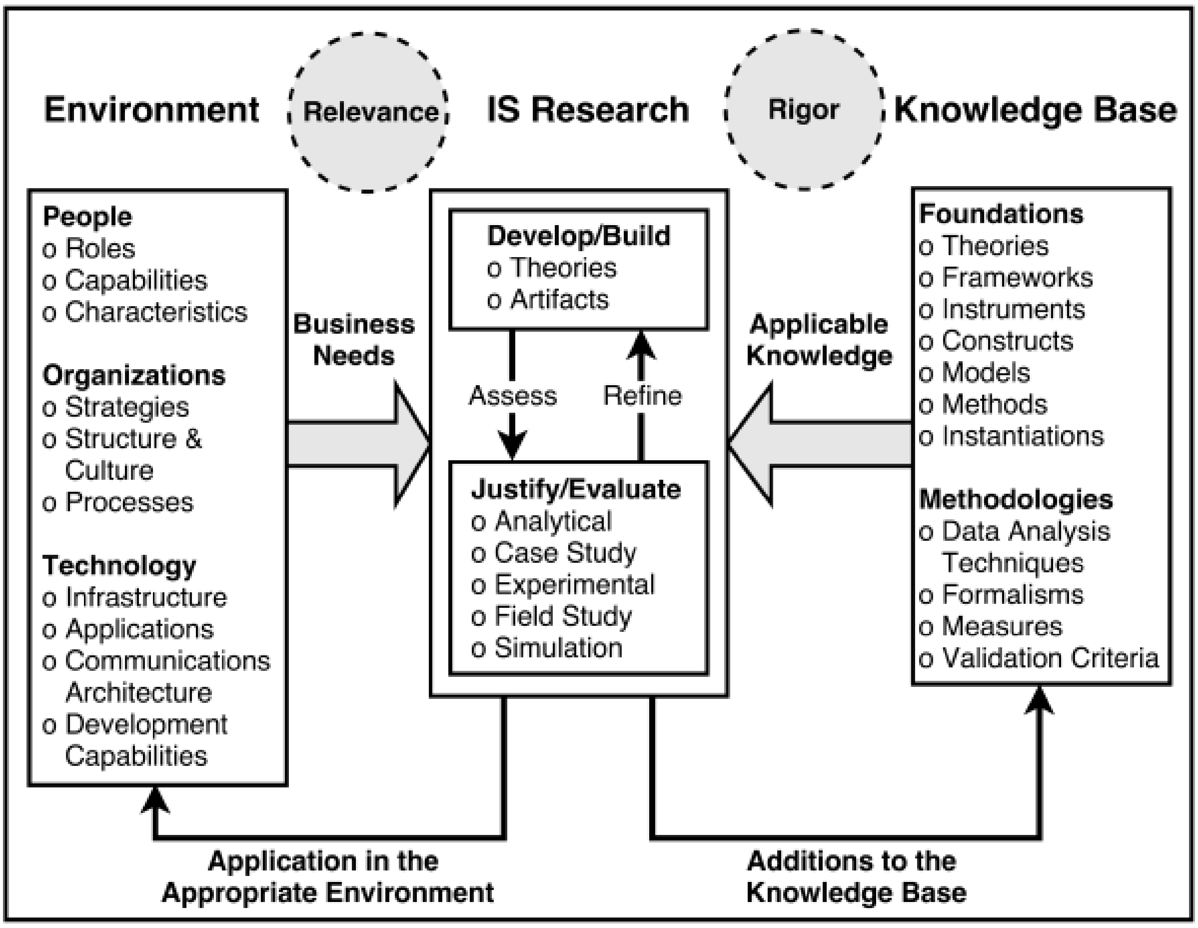

Figure 8 - Design Science Research Framework. Adopted from (Henver et al. 2004)

3.3 Design Science Research Guidelines

In their paper, Henver et al. (2004) provide a set of guidelines (Tbl. 5) to aid in the problem-solving process. However, they mention that these guidelines are there to assist the process, not to serve as mandatory steps for DSR. This allows for freedom in how to apply the guidelines in any setting. Sitepu (2017) chose to combine these guidelines into three cycles to address them easily and comprehensively. The first one is the relevance cycle, which covers the problem relevance (Guideline 2) and the research contributions (Guideline 4). The second one is the rigor cycle, which covers research rigor (Guideline 5) and design as a search process (Guideline 6). The third cycle is the design cycle, which encompasses the integration of the first two to create an artifact (Guideline 1), the evaluation of the design (Guideline 3), and the communication of the research (Guideline 7). In the next sections, the paper will cover how it will address the cycles of DSR as done in Sitepu (2017).

Guideline	Description
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of design artifacts.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Table 5 - Design Science Research Guidelines. Adopted from (Henver et al., 2004)

3.4 Relevance Cycle

Previous sections of this paper have discussed the significance of this problem. It was discovered that the city is not unlike a living organism and is a network of interconnected systems that must be in balance in order to prosper. Applying a holistic approach and linking these systems together in a system could enable self-regulation within the city. Having a system that can manage and adapt its operations in real-time based on data and simulations could bring a city closer to homeostasis. However, Kirwan and Fu (2020) found that it has been a major challenge to link all the systems inside a city together in one place. This paper tackles this challenge and develops a design for a holistic UDT that interconnects the whole city ecosystem, and through this, it will explore how UDT technology can enable city self-regulation. As the academic research on holistic UDTs is still limited, more insights on how to design such a system are needed. By addressing this, the paper will contribute to both the environment and build on the knowledge base of holistic UDT design as mentioned in Henver's framework (Fig. 8). It will contribute to the environment by giving guidance to parties that want to initiate the development of a holistic UDT, and it will contribute to the knowledge base by providing a base for further research into holistic UDT design

3.5 Rigor Cycle

This section will discuss the theoretical foundations and methods that make up the knowledge base, as well as the process of searching for an effective artifact.

3.5.1 Knowledge Base

The concept of a holistic UDT is relatively novel, with few existing theoretical frameworks available. However, in other industries, the use of DTs is widespread and more advanced. This paper aims to apply the lessons learned from other industries, particularly manufacturing, agriculture, and healthcare, to design a holistic UDT. Preliminary knowledge has already been gathered in the literature review. Given the limited academic literature on holistic UDT design, a thematic analysis was conducted to better understand the design's characteristics. This paper utilized the thematic analysis method as described by Caulfield (2022) and Verhoeven (2020) and is based on Braun and Clarke (2006).

The thematic analysis was applied to multiple sources that were gathered through desk research. These sources include academic and industry articles, books, reports, whitepapers, and policy briefs. Based on these a meta-architecture and initial design of the holistic UDT was created (Chapter 4). These were then refined and evaluated through expert interviews. Additionally, the empirical insights from the experts were used to design the components and revise the design of the holistic UDT (Chapter 5). The interview methods are addressed further in Section 3.5.3.

The paper applied a deductive approach to thematic analysis by comparing the data with preconceived themes based on the literature review. After collecting the data from various sources, the data were given codes to describe their contents after being collected from various sources. Similar content was combined to gain insights, which were then applied in the design process.

3.5.2 Search Process

Design is fundamentally a search process aimed at finding an effective solution to a problem (Henver et al., 2004). This paper does this by creating a design for a holistic UDT that enables self-regulation within cities. The propositions outlined in the previous chapter were the basis for the design and search process. First, to create a broader understanding of the proposed holistic UDT the context, goals, and scope were defined. Second, the ecosystem component was explored with a focus on who can use the system, who governs the system, and how collective intelligence can be integrated into the holistic UDT. Third, the self-regulation component was explored to what degree the system can become self-regulated and what data sources are needed to reach that goal. These three will comprise the research scope of the proposed holistic UDT in this paper. In short, this study looked to create a holistic UDT design that enables self-regulation within cities.

The study employed triangulation to ensure validity. The artifact was created by a combination of literature research, desk research, and expert interviews. Initial literature was mainly collected through ScienceDirect by using keywords like “Digital Twin”, “Urban Digital Twin”, “Smart Cities”, “Self-Regulation” and “City Ecosystem”. From the resulting papers snowball sampling was applied to find highly cited sources about the research topic.

Next, the desk research was completed by using the same keywords in Google’s search engine and looking for organizations that are working on Urban Digital Twins. Some reports or organizations were also found through word of mouth from the interviewed experts. Furthermore, the experts were sampled mainly through LinkedIn by using keywords like “Smart Cities” and “Digital Twins”.

3.5.3 Interview Methods

Next to desk research, this paper also used interviews as a primary method for data collection. As part of the design’s components creation and evaluation, 10 interviews were conducted. An unstructured interview approach was adopted to create an open conversation that allowed for more detail and nuance. The interviews were also explorative as not every interviewee had the same expertise. Some might have more expertise on the topic of smart cities and others might have more expertise on digital twin technologies. At the start of each interview, it was discussed what part the expert could offer their expertise on. When possible, insights from previous interviews were discussed to encourage an iterative and evaluative process, which is a key part of DSR (Henver et al., 2004).

The goal of the interviews was to use experts' insights to help evaluate the meta-architecture and initial design. Additionally, their insights were used to design the ecosystem-driven and self-regulation components. The experts were contacted by the author by email or LinkedIn and were given an overview of the research with general information on what the research was about and how their expertise could be beneficial. For this paper, both convenience and snowball sampling were applied. This was done because of the limited timeframe and availability of experts. This paper aimed to interview experts with extended knowledge in the field of smart cities or the field of digital twins. The descriptions of the interviewed experts can be found in Table 6.

All interviews were scheduled to last approximately an hour. Due to logistics and time constraints, the Interviews were held through Microsoft Teams, some were held in Dutch and some in English. Microsoft Teams was used to record and transcribe the interviews. To translate and summarize the interviews for the appendix, generative AI tools were utilized. To request the original interview recordings, please contact the author of this paper. For the paper itself, only the original recordings and transcripts were consulted. The summaries of the interviews can be found in Appendix IV.

Expert #	Description:
1	The Program Manager for the Digital City and Digital Twin projects in the city of Rotterdam, the Netherlands with expertise in governance, digital twins, and open urban data platforms
2	A Technology Advisor and member of the Council of Cities for OASC, a European organization for open & agile smart cities & communities with expertise in open standards
3	The Program Manager for the Digital Twin project in the city of Utrecht, the Netherlands with expertise in digital twin technology
4	A Smart City Director at a large sustainable area development company, and construction company in the Netherlands with expertise in sustainable city development and sustainable transition
5	An academician in the field of Geomatics with published works on urban digital twins, aligned with a major public university in Wallonia, Belgium
6	A System Coordinator Basisregistraties in a medium-sized municipality in the Netherlands with expertise in municipal data coordination
7	A Project Manager IT & Smart Cities at a Flemish organization with expertise in digital transition in municipalities
8	A Smart City Advisor & Consortium Coordinator of smart city-related EU projects and co-author of a plethora of reports for the organization Digital Urban European Twins
9	A Digital Twin, GeoBIM, and Standardisation Advisor for large Dutch municipalities like Rotterdam, the Netherlands
10	A principal data & AI scientist and thought leader of Digital Twins at a large multinational in the area of health technology situated in the Netherlands

Table 6 - Expert List

3.6 Design Cycle

The design cycle includes the creation of the artifact, its evaluation, and the research communication. The knowledge base developed in earlier cycles was utilized to create a comprehensive holistic UDT design. This design will serve as the DSR's artifact. Henver et al. (2004) describe artifacts created in DSR as innovations defining ideas, techniques, and products that facilitate the analysis, design, implementation, and use of information systems, rather than being full-fledged systems used in practice.

In Chapter 4 the meta-architecture and an initial design of the system will be created based on the knowledge gained from the literature review and desk research. In Chapter 5 the components will be designed and a revised design of the system will be created based on a combination of literature, desk research, and expert interviews. In both chapters, each variable of the design part of the conceptual model will be discussed. Additionally, each component will produce design choices for the artifact, these will be displayed in a table at the end of the chapters.

Given the novel concept of a holistic UDT that encompasses the ecosystem and self-regulating components, there are no existing artifacts of the same scope for comparison, similar to the situation in Sitepu (2017). This implies that comparative measurement evaluations of the artifact are not yet possible. Furthermore, the holistic UDT's complete creation and implementation are beyond the scope of this paper. To evaluate the artifact, this paper has employed the informed argument method as described by Henver et al. (2004), which involves using information from the knowledge base to construct a compelling argument for the artifact's utility. The design presented in this paper will serve as a foundation for further research and development of a holistic UDT.

4 Holistic Urban Digital Twin Design

A holistic urban digital twin is more than just a 3D model of a city, it is a complex system that engages the entire city ecosystem. The more complex a system is the more difficult it is to understand (Broy et al., 2009). This chapter aims to create a clear understanding of the system so it can be communicated to all stakeholders. This will be done by applying the principles of meta-architecture. To create this shared vision, the context, goals, scope, stakeholders, and architectural strategy will be discussed. At the end of this section, the design choices will be described.

4.1 Meta-Architecture

4.1.1 Context

The context will be described by giving a system overview of the proposed holistic urban digital twin.

Just like a living organism, the city needs to constantly adjust to internal and external conditions. Therefore the city needs to be able to regulate its operations in real-time, by responding to all functions at the same time in harmony. This harmony is also called "homeostasis". This homeostasis is defined as a self-regulating process by which a living organism maintains internal stability while adjusting to changing external conditions (Mas-Bargues et al., 2023). To ensure "urban homeostasis," self-regulating systems must be built. Harnessing the collective intelligence of a city ensures that homeostasis is maintained, and all systems are working together seamlessly. Combining collective intelligence and AI will allow cities to become self-regulating through sensors, data analytics, and real-time processing of city operations (Kirwan & Fu, 2020).

When viewing the city as a living organism, comparisons can be drawn between the functions of a city and those of the human body. Within this analogy, the proposed urban digital twin would be the cerebral cortex of the city serving as an operating system managing and adapting its operations based on real-time data and simulations and thus shall be called "*CityOS*".

CityOS is based on Digital Twin technology, which collects data, processes it, and generates a digital version of the city from where it can be used to manage the city, simulate interventions, and actuate these interventions back to the city (Lei et al., 2023; Talkhestani et al., 2019). It enables the use of different digital twin types, be they imaginary, monitoring, predictive, prescriptive, autonomous, or the recollection variant. Thus creating a space where the city can be represented in all of its possible states.

CityOS is meant to progress the city towards the automation and self-regulation of its operations and assist in evidence-informed decision-making. As CityOS evolves, it will gain the ability to autonomously monitor the city for inconsistencies with the United Nations SDGs, City KPIs, or other city ambitions and simulate and actuate suitable interventions. Autonomously self-regulating operations in real-time to achieve urban homeostasis (Verdouw et al., 2021; Talkhestani et al., 2019). Additionally, CityOS enables evidence-informed decision-making for stakeholders by providing data based on simulations.

CityOS goes beyond representing the physical realm; it also captures the human dimension of the city to simulate the decisions, behaviors, and interactions of its citizens. By doing this CityOS can support decision-making on fronts such as inequality and socioeconomic development (Birks et al., 2020).

Following smart city principles, CityOS harnesses technology to establish transparent, fair, and inclusive mechanisms enabling greater social participation to drive forward the modernization of society (CAICT & EUCPDSF, 2016). Opening up the data of the public and private sectors to bring down knowledge barriers enhances the city's collective intelligence.

CityOS requires a collaborative approach to governance to bring together public, private, and community stakeholders to engage in consensus-oriented decision-making (Ansell & Gash, 2007). Furthermore, CityOS can be seen as a living lab for the city where co-creation, co-design, and communal development boost innovations in the city ecosystem (Kirwan & Fu, 2020).

In summary, CityOS resembles a city's central nervous system, a system where the city's collective intelligence comes together to manage operations in real-time based on data and simulations to achieve urban homeostasis.

4.1.2 Goals

The core objective of CityOS is to unify the city ecosystem so that cities can manage and adjust their operations in real-time using data and simulations. This objective stems from the overarching objective of achieving a state of urban homeostasis: a state of balance in nature, the well-being of its people, and the optimization of technology (Kirwan & Fu, 2020).

Additionally, CityOS creates a sense of sharing, transparency, equality, social participation, innovation, and openness within the city (CAICT & EUCPDSFII, 2016).

Moreover, CityOS can be instrumental in achieving the Sustainable Development Goals set by the United Nations (2015). The system can be a tool to help with decision-making towards these goals.

Furthermore, CityOS should stimulate the creation of collaborative and innovative solutions to societal challenges like the Sustainable Development Goals set by the United Nations (2015)(Ruston McAleer et al., 2020). CityOS is designed to enable evidence-informed policy and decision-making to reach the city's ambitions.

Finally, CityOS is a living lab to be a collaborative incubator for the whole city ecosystem enhancing the collective intelligence of a city.

4.1.3 Scope

In this section, the focus and boundaries of the system will be described. The focus and boundaries of the system are viewpoints that distinguish what is and what is not part of the proposed system (Broy et al., 2009).

Focus of CityOS

The focus of CityOS is to offer the city a platform that encapsulates as much of the city ecosystem as possible to enable self-regulation in the city. Its primary function is to interconnect the city's physical, social, and technological realms to enable the creation of comprehensive digital representations of the city and enable simulations of interventions. The system focuses on:

- Real-time and static data integration from different urban data sources such as IoT sensors, existing data sets, sentiment analysis, crowdsourced monitoring, etc.
- An as-close as possible mirror of urban life in all its complexity. From systems and subsystems both above and below ground (Raes, McAleer, et al., 2022)
- Facilitating evidence-informed decision-making through different types of simulated models, such as present, past, or future models of the city.
- Allowing for an interface for stakeholders to engage with the system to collect insights from the city's digital twin.
- Enabling cooperation between all stakeholders in a city to solve societal issues.
- Providing base models for city stakeholders to develop for their use cases.
- Establishing a continuous feedback loop between the physical and virtual environment.

Boundaries of CityOS

The boundaries of CityOS are:

- Geographical limitation: The system is constrained by city boundaries, but it should be scalable as the city grows
- Functional Limitations: CityOS does not replace all individual city functions, but rather seeks to assist stakeholders in their operations.
- It won't be a single twin model but rather an ensemble of cooperating twins (Raes, McAleer, et al., 2022)
- Data Management: The system should adhere to strict data protocols adhering to strict privacy regulations and ethical standards which are monitored by the collaborative governance board.
- Technological Frontiers: While innovative the system respects the current state of technology and can only operate within the realm of what is practically possible.

4.1.4 Stakeholders

The quadruple helix model of innovation is frequently used to describe the four major actors in a city. These are public organizations, citizens & communities, academia, and private organizations (Schütz et al., 2019; Sheombar et al., 2020)(Fig. 9). These four are the main stakeholder groups that can all fulfill the role of the data provider, system user, or system operator. As emphasized by Dai et al. (2024) when working toward smart city transformation, all stakeholders need to interact with each other during the process of transformation. In Chapter 5.1 more detail will be discussed on the role these stakeholders play.

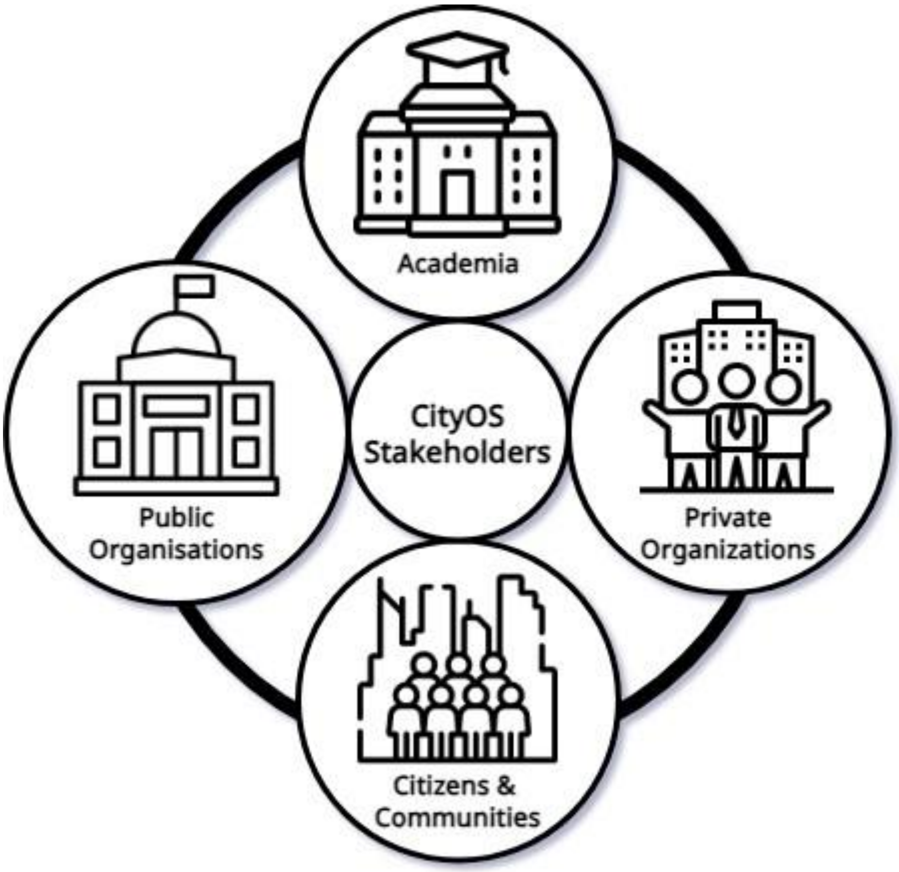

Figure 9 - CityOS Stakeholders

4.1.5 Architectural Strategy

In this section, the architectural strategy for the system will be defined by defining the guiding principle, capabilities, architectural patterns, and possible technical considerations.

Guiding Principle

The development of CityOS, which is conceptualized as the city's central nervous system, is guided by the assumption that the city is a living organism. This is highlighted by the continual evolution of cities (Kirwan & Dobrev, 2022). Following this assumption, the design of CityOS follows the principle of "form follows function"(Kirwan & Fu, 2020). This principle means that the system architecture must reflect and facilitate the dynamic flow of a city. The overarching goal of CityOS is to achieve urban homeostasis, by balancing environmental sustainability, societal well-being, and technological optimization. To this end, the system aims to enable the city to reach these goals through evidence-informed policymaking and data-driven decision-making.

Capabilities to be Built

For CityOS to reach its objectives, it must be able to perform a series of capabilities of an advanced digital twin. These capabilities are based on the works of Lei et al. (2023), Verdouw et al (2020), and Talkhestani et al. (2019) as they provide extensive knowledge of advanced DTs.

- **Data Integration**: the system must be able to aggregate dynamic and static data from different sources, including IoT sensors, data sets, and sentiment analysis.
- **Model generation**: The system must be able to transform the collected data into digital representations of the city, facilitating both current state monitoring and future state simulation.
- **Simulation and Actuation**: The system must be able to simulate interventions within these models to inform decision-making around policies and actuate operational changes in the real city.
- **Open Standards Utilization**: The system must commit to using open standards to ensure compatibility and interoperability within and beyond the city's systems.
- **Synchronization**: The system must be able to detect changes within the city and update these changes in the models dynamically.

System Attributes

Ferko et al. (2022) analyzed 140 papers and consulted experts to find the most important attributes digital twins need. This paper will use these in combination with the attributes mentioned in Verdouw et al. (2020). As they created an advanced design for autonomous DTs which this paper seeks to adapt to the urban context. Therefore CityOS should have the following attributes:

- **Interoperability and Compatibility**: The system must be able to communicate with a plethora of different systems.
- **Scalability**: The system must be able to accommodate the city's growth without compromising performance.
- **Maintainability**: The system must be able to be maintained without significant downtime or cost.
- **Reconfigurability**: The system must be able to be reconstructed to adapt to changes in technology or regulations.

- **Extensibility**: The system must be able to handle new functionalities without compromising the existing system.
- **Fidelity**: The system must maintain accuracy and precision when simulating real-world scenarios. Accuracy is crucial if the system is to be used for decision-making.
- **Performance efficiency**: The system must be optimized to maximize the use of resources, such as processing power.

Architectural Patterns

Despite the plethora of architectural solutions for DTs a study by Ferko et al. (2022) shows that most DTs only use a few different patterns. The patterns most commonly used for DTs are either layered, service-oriented architecture (SOA), component-based, or hybrid between them. Next to that Rizwan et al. (2023) write in their paper that a federated approach for the simulation parts of the Digital Twin could ensure data privacy for parties while still being able to produce results for CityOS.

- **Layered Pattern**: This pattern is the most common pattern used in system architecture as it organizes the system into clear functional layers each performing a specific role. Its main feature is the separation of concerns between components which makes it easy to develop, test, govern, and maintain the system (Richards, 2015; Ferko et al., 2023).
- **SOA**: SOA increases interoperability, allowing modular services to be reused across CityOS' network. Each service provides a capability and services can communicate across the platform (AWS, n.d.; Ferko et al., 2023).
- **Component-Based Architecture**: This pattern increases the maintainability and extensibility of CityOS by enabling it to be composed of interchangeable, reusable components. This modular approach ensures that when CityOS needs to evolve only specific components need to be altered or replaced without a complete system overhaul. (Ferko et al., 2023; Gillin, 2024)
- **Federated Learning Pattern**: using this approach, CityOS can process data locally at the source and only share model updates instead of raw data. This respects citizens' privacy as the raw data never leaves its local environment. Each stakeholder that has built its solution as an add-on to CityOS can run its simulations and only share the insights gained from the simulations with the system keeping data used locally (Rizwan et al., 2023).

Therefore this paper suggests the adoption of a hybrid pattern between layered, SOA, component-based, and federated learning to ensure the system remains scalable, maintainable, interoperable, flexible, and privacy-compliant which ensures that the system can meet the evolving demands of the city.

Technical Considerations

According to Kirwan and Dobrev (2022), a hybrid configuration of centralized, decentralized, and distributed systems deployed across physical and digital dimensions could be the answer to support the complex system and distribute the system load. An example could be that the base CityOS is hosted centrally, but extensions for specific use cases can be hosted at the party that uses it (Fig. 10).

Additionally, CityOS could be built on a public stack. Which can be seen as an open, democratic, and sustainable digital space. Instead of building the system in a private or state-owned stack where privacy can not always be assured and citizens don't have any voice, the principles of a public stack could be followed. A public stack puts public values at the center of the design. It relies on open technology, open design processes, and common values (Waag Futurelab, 2024). Creating a CityOS for the ecosystem would benefit a lot from these principles as they directly impact transparency, democracy, equality, and citizen participation in the system.

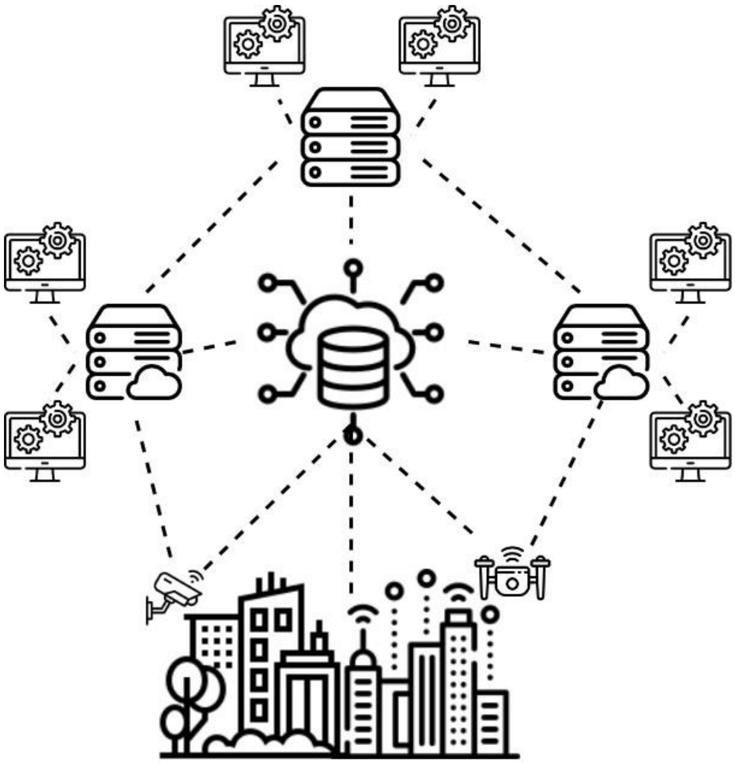

Figure 10 - Hybrid Topology CityOS

4.1.6 Design Choices: Meta-Architecture

This meta-architecture provides a high-level overview of the system. This overview can be used to help align stakeholders and start the system's development. In Table 7 the design choices that stem from the meta-architecture will be shown.

Design Choice #	Description
1	CityOS should be seen as the cerebral cortex of the city
2	CityOS is based on digital twin technology
3	CityOS enables the use of imaginary, monitoring, predictive, prescriptive, autonomous, and recollection digital twins
4	CityOS should monitor the different states of the city autonomously to find inconsistencies with the city's ambitions
5	CityOS should capture both the physical realm and the human realm of the city
6	CityOS follows smart city principles to establish transparent, fair, and inclusive mechanisms
7	CityOS' core objective is to unify the city ecosystem to empower cities to manage and adjust their operations in real-time based on data and simulations
8	CityOS focuses on one city's ecosystem and is bounded by the city limits
9	CityOS' main stakeholder groups are public organizations, citizens & communities, academia, and private organizations
10	CityOS' architectural guiding principle is 'form follows function' to reflect the dynamic flow of the city
11	CityOS should have the capability to integrate data, generate models, simulate and actuate interventions, utilize open standards, and synchronize the digital twin with the real-world
12	CityOS should be interoperable, compatible, scalable, maintainable, reconfigurable, extensible, fidelity, efficient
13	CityOS should adopt a hybrid pattern between layered, SOA, component-based, and federated learning to ensure scalability, maintainability, flexibility, interoperability, and privacy-compliant
14	CityOS should adopt a centralized, decentralized, and distributed hybrid topology to support the complex system and distribute system load.
15	CityOS should be built on a public stack if possible to increase transparency, democracy, equality, and citizen participation in the system.

Table 7 - Design Choices Meta-Architecture

4.2 Initial Design

To explain how CityOS works in more detail, this paper presents an initial design (Fig. 11) that is based on the agricultural digital twin design by Verdouw et al. (2021) and adapted to fit the current context. This was done because their design showed a clear overview of an advanced digital twin that can work autonomously. This initial design served as an initial artifact, so it could be evaluated with the help of experts. First, all the separate parts of the design will be described. Second, a description of how the system operates will be given.

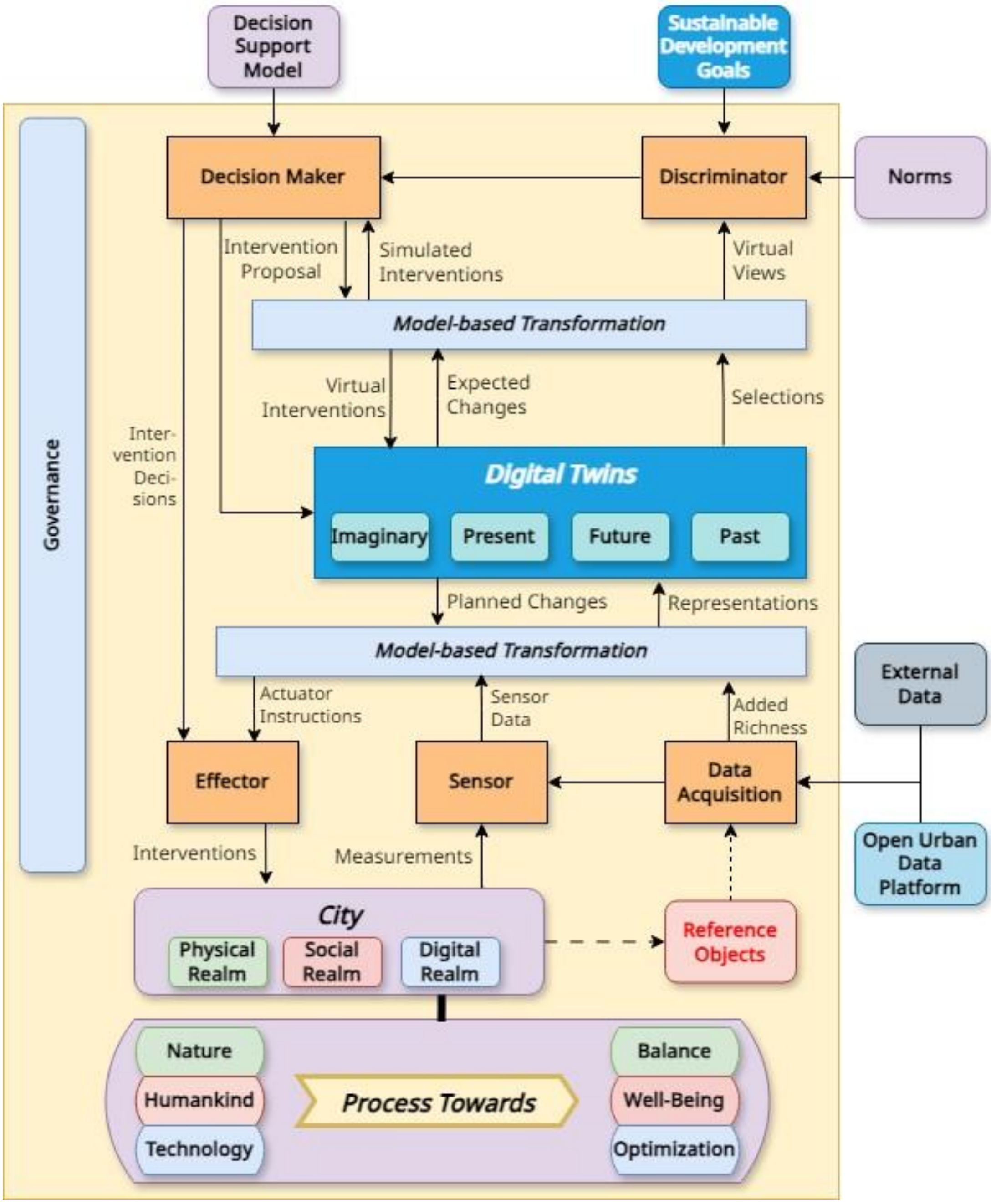

Figure 11 - Initial Design for CityOS.

Parts Description

Process Towards depicts the objective evolution of the city's different realms. It is the city's ongoing process to achieve balance in nature, human well-being, and technology optimization.

The city represents the city as a whole and the three defined realms that it contains. These are the “objects” to be virtualized and simulated in the Digital Twin.

Reference objects represent “objects” that do not yet exist in reality this allows for the representation of conceptual entities. Think of a to-be-realized building or road that needs to be simulated to test how it will affect the rest of the city.

The sensor represents the measurement tools that the system uses to provide a (near) real-time flow of data on the current state of the city.

Data acquisition represents the acquisition of data that does not come directly from sensors in the city, this data can come from data collected on an urban data platform or external data from outside of the city ecosystem.

Model-based transformation is where the data is transformed into a representation based on a meta-model which is a model that gives instructions on how the model should be formed.

The digital twin is the digital representation of either an imaginary, present, future, or past state of the city. These are the digital twin types as described by Verdouw et al. (2020) as mentioned in Section 2.2. Every representation can exchange data with one another.

The discriminator function compares the measured state of the DT with set norms that specify the desired state of the city and signals deviations to the decision-making function. These norms can either be sustainable development goals translated into KPIs or other norms relating to the DT's specific use case.

The decision-maker selects the appropriate interventions for desired changes based on a decision-support system.

The effector is the function in the system that implements the selected interventions in the real world.

Description of System Operation

The design in Figure 11 shows that the cycle starts with measuring the city's physical, social, and digital realms. This is done by collecting sensor data and data from external sources. Next to this reference objects can be used for not-yet-existing objects. This data is then transformed into a virtual representation of the city based on a meta-model. This can either be an imaginary, present, future, or past representation of the city. The Digital Twin will then include all relevant information for the specific use case of the Digital Twin. Depending on the purpose of the model some irrelevant information can be filtered out so it can be presented in a way that users can easily process the information. Following this, the discriminator compares the city's state with established norms such as the SDG KPIs by U4SSC (2017). Any deviations from the set norms will be communicated to the decision-maker function. Finally, the decision-maker, which can be both human and non-human selects the appropriate intervention based on its decision-support model. This depends on what type of DT was used. In the case of prescriptive DTs, the intervention proposals will be simulated into a future model of the city, so a human decision-maker can use this to decide the final intervention. In the case of autonomous DTs, they would do the same thing, but on top of that, they would also translate the intervention decision into planned changes and subsequently into actuator instructions. Autonomous DTs remote control the effector function that executes the instructions and implements the interventions in the city (Verdouw et al., 2021). And after this, the cycle will begin anew.

5 Design Components

This section will discuss the components—which can be seen as the parts of the mediator variable— proposed to be needed to enable self-regulation in the city. First, the ecosystem-driven component will be discussed. Second, the self-regulation component will be discussed. Lastly, at the end of each section, the design choices will be described. From, this point on next to literature and desk research also the knowledge from experts will be used to discuss the components.

5.1 Ecosystem-Driven

This section will describe the ecosystem component by describing how CityOS is built on the collective intelligence of the city, how CityOS is used, and what the governance structure of CityOS looks like.

5.1.1 Collective Intelligence

One of the main objectives of CityOS is the utilization of technology to adhere to smart city principles (Section 2.1). To achieve this, CityOS needs to harness the collective intelligence of a city and thus engage the whole ecosystem. To harness the collective intelligence of a city the system needs to be treated as a living lab where the ecosystem of the city can collaborate in the development and innovation of the system (Kirwan & Fu, 2020). Designing CityOS as a living lab would facilitate collaboration and co-creation between ecosystem stakeholders.

This approach would be called a network-owned system as described by D'Hauwers and Kogut (2021). This means that the system is open for the ecosystem to use and the control is decentralized by the ecosystem. According to Expert 8, this approach would be the most sustainable way of setting up a UDT. The expert mentioned that currently, the commercial sector is trying to sell DT systems as an out-of-the-box solution, but this would not be good as it would severely limit the potential use cases.

Additionally, Expert 2 would choose to go with an open approach to avoid commitment to a single monolithic technology provider. Expert 3 supports this by stating that a vendor lock is not desirable for cities. If a city were to leave its digital infrastructure mostly in the hands of private companies, this could lead to the city becoming too dependable on these companies. Expert 1 states that if this happens "We as a municipality will end up as a customer in our own city." The expert believes that from a democratic perspective, this would not be desirable. Furthermore, Expert 2 also believes depending on one company will likely result in limited transparency and a lack of open standards.

Experts 2 and 6 believe that it would be better to modularize the system by combining different open-source tools that can be integrated into the system. Expert 8 would agree with this, saying that they believe at least a base version of CityOS would need to be open to the ecosystem and be governed by the ecosystem. In this base version, the expert mentions that at least a full 3D model of the city should be included with all the infrastructure networks and a base amount of sensors throughout the city connected to this model to keep it up to date. They believe that the foundation of CityOS should allow for the integration and pairing of various data sets to cater to specific use cases. The expert mentions the same about simulation models, in their experience, they used a federated approach where they combined simulation models from different providers to create a complete picture of their use case. Expert 5 supports this by saying that in contrast to the past, an increasing number of cities are collaborating on city models. Additionally, Expert 8 says that to use this approach it is vital to ensure open standards are used so every module can communicate efficiently with another.

Kirwan and Fu (2020) support this by saying an open-source approach to the system would allow for more flexibility and adaptability to the city's ever-changing environment. They state that to engage citizens and gather valuable feedback this kind of system should be open to all citizens. It would allow for the needs of the citizens to be incorporated into the management and operations of the city (White et al., 2021). Expert 3 also believes that an open-development approach would be beneficial. In their own UDT project, all code is open, so people can participate in the development of the system. In contrast, Expert 9 also mentions a downside of an open-source approach, which is that there is no party to look at when development gets stuck or new functionalities need to be built, which is different from having a service-level agreement with a supplier.

Expert 1 states that the city is not only its municipality but a whole ecosystem containing all kinds of stakeholders that are connected in some way. By engaging the whole ecosystem CityOS would allow for wider groups of stakeholders to become part of the ecosystem (Raes, Bouchal, et al., 2022). Citizens can have much greater influence over policy processes than just being on the receiving end of the decisions made. According to Raes, Bouchal, et al. (2022), allowing stakeholders to review, tweak, and propose alternate plans, would not only improve public policies but also strengthen the link between government and society. Additionally, Expert 2 adds to this by stating that by eliminating backroom discussions making policy-making more transparent, and explaining why certain decisions are being made, you develop more support and trust from within the population.

In summary, designing an ecosystem-driven CityOS is important to incorporate the collective intelligence of a city and enable a collaborative innovative, and equally accessible environment. The consulted experts unanimously tilt toward an open modular system that prevents vendor lock-in and promotes transparency and ecosystem inclusion. Therefore CityOS is to be a living lab allowing for co-creation and co-development of the system. Additionally, CityOS should be developed openly and modular to prevent vendor lock-in.

Finally, CityOS should offer base models and functionalities to all city ecosystem stakeholders.

5.1.2 Usage

Opening CityOS to the ecosystem would not only promote openness and democracy but also enable stakeholders to use the system to create new value propositions for both public and private use cases. By developing an open CityOS as a foundational UDT system that provides the necessary components for users to customize for specific use cases, stakeholders can avoid duplicating efforts for each use case. To better display this idea, Expert 5 recommended creating use cases to make the concept and system better understood by stakeholders. Additionally, Experts 8 and 10 also support this by saying that it is vital to have clear use cases to convince investors and users of the possibilities that the system provides. Therefore, in Appendix V, use cases for each of the stakeholder groups are presented. These use cases have been created to make CityOS more tangible by giving clear examples of how the system can be used by each stakeholder group.

Concluding, it is suggested that CityOS should be able to be used by all ecosystem stakeholders for various applications. The use cases presented are only a few of the possible use cases for how CityOS can be used by stakeholders. By using the ecosystem-driven approach CityOS can be seen as a platform for innovation, allowing various stakeholders to collaborate on the future of the city. Therefore, CityOS should be accessible to all city ecosystem stakeholder groups to promote inclusivity. Additionally, CityOS' stakeholders should be able to create value by using the system for both public and private use cases.

5.1.3 Governance Structure

In an ecosystem-driven CityOS, governance plays a crucial role in guarding the balance between commercial exploitation and the societally responsible behavior of actors in the ecosystem (D'Hauwers et al., 2021). To engage the whole ecosystem a collaborative governance approach is needed (Ansell & Gash, 2007; Raes, McAleer, et al., 2022). This approach should promote cooperation and knowledge sharing between different stakeholders and at the same time keep the wider community informed and engaged (Raes, McAleer, et al., 2022).

Expert 5 explains that no one person can have expertise on every topic, which is why collaboration is needed. The expert gave an example of how the University of Munich manages complex projects by relying on extensive collaboration between departments. This is supported by Expert 4 who states that it will be important for different parties to collaborate and share data to effectively reach their goals.

Expert 1 talks about how Rotterdam currently organizes the governance of its open urban data platform, which is seen as a central junction of the city's digital infrastructure. According to the expert, this platform allows the city's ecosystem to exchange data responsibly. To govern the platform, they installed a governance board consisting of public and private parties from the ecosystem that supervise the platform and make up its rules. The expert explains that governance is needed to ensure that the platform is being used ethically and responsibly. They elaborate by explaining that in most digital developments, legislation and regulations are always behind, and there is no way to enforce the responsible use of the platform. Because of this, the expert believes that a governance board that decides collaboratively what can and cannot happen on the platform is necessary. The governance board in the case of Rotterdam currently consists of five independent individuals with different backgrounds. It consists of people from academia, civil society, industry, and government, and they have budgetary space to involve external expertise if needed. When asked the question, Experts 8 and 9 also believe that a system such as CityOS should be governed by the ecosystem through the means of a governance board with members from all stakeholder groups.

While establishing a governance board for CityOS is an important move that can ensure that the system is governed democratically, it is highly recommended that the board follow existing principles to guide its decisions. One group of existing guiding principles is the Gemini Principles, which are intended to help the industry develop DTs in an aligned way so they can be used in an existing ecosystem (Bolton et al., 2018). There are 9 principles, divided into 3 categories.

The first category is 'Purpose', which states that the DT created must have a clear purpose. Within are the following principles:

- Public Good: must be used to deliver genuine public benefit in perpetuity.
- Value Creation: Must enable value creation and performance improvement.
- Insight: Must provide determinable insight into the built environment

The second category is 'Trust', which states that the DT must be trustworthy. Within are the following principles:

- Security: Must enable security and be secure itself.
- Openness: Must be as open as possible.
- Quality: Must be built on data of an appropriate quality.

The third category is 'Function', which states that the DT must function effectively. Within are the following principles:

- Federation: Must be based on a standard connected environment
- Curation: Must have clear ownership, governance, and regulation.
- Evolution: Must be able to adapt as technology and society evolve.

Following these principles can help the governance board in their decision on whether to accept a new use case of CityOS.

Next to these principles, CityOS should also use and promote the use of open standards. Almost all experts mentioned that this would be an integral part of the success of the system (Experts 1, 2, 3, 5, 6, 7, 8, 9). This is because interoperability is the greatest challenge that UDTs have to overcome. This is because CityOS is a central system that relies on different types of data, all of which can come from different places. For all the parts of CityOS to communicate and share data, there is a need for standards (OASC, 2023). Standards-based interoperability facilitates communication between systems like IoT sensors and simulation models (Raes, McAleer, et al., 2022)

To address this, organizations like OASC (Open & Agile Smart Cities & Communities) work to create open standards for smart cities. In the case of OASC, these open standards are called MIMs (Minimal Interoperability Mechanisms). These MIMs are vendor-neutral and technology-agnostic, meaning that anybody can use them in their system, so their systems will be able to 'talk' with other systems with the same open standards. Experts 1 and 2 both mentioned OASC as one of the main organizations driving open standards development. The use of open standards, such as those from OASC, can allow the system to exchange data more easily and quickly. Expert 1 specifically describes open standards as a way for systems to share a common language so they can communicate with one another. Expert 8 adds to this by stating that open standards are not only important for data integration but also for simulation outputs, as the outputs of simulations need to be able to be understood by other parts of the system. Next to this internal messaging of the system, there would also be a main part where open standards are needed. Open standards are, according to most experts, the key to achieving interoperability in the system (Experts 1, 2, 3, 5, 6, 7, 8). The system's governance board must decide which open standards will be used and enforce their use to ensure interoperability within the system.

Concluding, CityOS should adopt a governance board with representatives of all stakeholder groups. This governance board should be guided by principles like the ones described above. This governance board must ensure that CityOS is operated ethically and responsibly. Furthermore, CityOS should make use of open standards to ensure interoperability throughout the system.

5.1.4 Design Choices: Ecosystem-Driven

Concluding the discussion on the ecosystem-driven components, it is evident that CityOS is envisioned as a collaborative, open, and modular system that harnesses a city ecosystem's collective intelligence. By engaging the whole ecosystem, CityOS ensures its sustainability. Experts unanimously agree on the necessity for CityOS to support different use cases from all stakeholders. They also agree that collaboration between the ecosystems is important for the system's success. Lastly, all experts advocate for using open standards to ensure interoperability within the system. The design choices of this component are displayed in Table 8.

Design Choice #	Description
16	CityOS is to be a living lab allowing for co-creation and co-development of the system
17	CityOS should be developed openly and be modular to prevent vendor lock-in
18	CityOS should offer base models and functionalities to all city ecosystem stakeholders
19	CityOS should be accessible to all city ecosystem stakeholder groups to promote inclusivity
20	CityOS' stakeholders should be able to create value by using the system for both public and private use cases
21	CityOS should adopt a governance board consisting of representatives of all stakeholder groups to promote cooperation and knowledge-sharing
22	CityOS' governance board must ensure that CityOS is operated ethically and responsibly
23	CityOS' governance board should use guiding principles like purpose, trust, and function to decide on use cases of the system
24	CityOS should use open standards throughout the system to ensure interoperability

Table 8 - Design Choices Ecosystem-Driven

In the following section, the self-regulation components will be discussed, exploring to what extent CityOS can enable self-regulation of the city and what the data characteristics of CityOS are.

5.2 Self-Regulation Components

As mentioned before, the self-regulation of a city refers to the ability of a city to manage and adapt its operations in real-time based on data and simulations. This definition does not prescribe whether human interaction in the process of management and adaptation is required. Consequently, this chapter will examine to what extent self-regulation can be actualized both with human interaction and without. Additionally, the data characteristics of CityOS will be discussed and described.

5.2.1 Extent of Self-Regulation

This section will describe to what extent self-regulation in a city can be achieved through CityOS. First, CityOS will be compared to a maturity model to determine its capabilities in UDT literature. Second, the current decision-making process of a city will be described. Third, CityOS and human interaction will be described. Fourth, CityOS will be described without human interaction. Fifth, the guiding principles for artificial intelligence use in cities will be described. Finally, the current European regulations around artificial intelligence in relation to CityOS will be discussed.

Maturity Model for Urban Digital Twins

In 2024 Haraguchi and colleagues created a maturity model showing the 8 different stages a UDT can be in (Appendix VI). Comparing this paper's definition of self-regulation with the maturity model, it can be stated that self-regulation with human involvement starts at stage 6, and autonomous self-regulation starts at stage 7. The maturity model states that a UDT reaches stage six when it can analyze dynamic and integrated 3D data, offering accurate insights and real-time alternative options for decision-making. Additionally, the UDT should be able to simulate the impacts of interventions across different domains. Furthermore, the maturity model shows that a UDT reaches stage 7 when it can use autonomous reasoning and AI to make independent decisions and execute actions based on predictions and simulations.

Current Decision-Making in Cities

Currently, cities make decisions that can be categorized into three types: operational, tactical, and strategic. Operational decisions cover activities such as traffic management, heat regulation, and waste collection scheduling. Moving towards tactical decisions that involve actions like granting permits for urban development and planning infrastructure maintenance. At the highest level, strategic decisions revolve around determining locations for new infrastructure and establishing sustainability goals.

Expert 4 mentions how currently most tactical and strategic decisions in the city are made based on the traditional way of letting an external party create a report that contains details and advice on what should be done in the city. Expert 9 supports this statement by adding that these kinds of reports cause difficulties when needing to explain the changes to stakeholders. The expert gives the example of a report of 500 pages in which only a small group fully understands what is written. He adds that visualizing the proposed changes would already be a great improvement on current decision-making as it makes it easier to communicate with stakeholders. Moreover, expert 4 recalls a case where during the development of a neighbourhood in the Hauge it was by chance found that there was no higher educational institution nearby. This implied that the neighborhood's lack of easy access to education could have significantly contributed to its prosperity or the lack thereof. Instead of accidentally coming across these facts a place where policymakers have a holistic visual overview of the city could improve decision-making towards improving the well-being of citizens. Expert 3 also mentions that the transition towards DTs as a way to display the whole city in relation to itself can be very effective. The expert mentions how a 2D model of a city is very limited because of all the layers that exist in a city like the electricity grid, sewage system, and mobility network. They emphasize that this is why it is important to move towards 3D city modeling.

CityOS at Stage 6: Self-Regulation with Humans

In the sixth stage, CityOS gains capabilities to analyze dynamic and integrated 3D data, offering accurate insights and real-time data for decision-making. And can simulate impacts across different domains (Haraguci et al., 2024). This implies that there is self-regulation as the city can manage and adapt its operations in real-time based on data and simulations. Enabling self-regulation in cities would enhance day-to-day city operations by helping managers react quickly to real-time events, and harness the collective intelligence of all stakeholders to tackle complex policy problems (Ruston McAleer et al., 2020). Expert 8 says that currently, DTs are mostly seen as 3D models. They mention that people are not aware of the predictive and prescriptive policymaking capabilities a DT can provide. The expert suggests that DTs could help contribute to streamlining the policy-making cycle by enabling evidence-informed decision-making.

Evidence-informed decision-making can be achieved through predictive and prescriptive DTs. Predictive DTs project the future state and behavior of the city's real-life objects. Here, future states can be forecasted by using prediction models. The prediction model uses information on the current and historical states of the city in combination with external data to project the future state of the city (Verdouw et al., 2021). Expert 10 mentions that in their use case, they also use a combination of historical data, current data, and external data to forecast the object's future state. An example of this would be monitoring an object with a component that needs maintenance if it reaches a certain temperature. By combining the historical temperature of the object with the current temperature, a forecast can be made for when the object will reach its maintenance temperature. Translating this example to the city, CityOS could self-diagnose by monitoring the city and finding any inconsistencies or opportunities based on the city’s ambitions.

Prescriptive DTs represent the effects of interventions in a present DT on a future DT (Verdouw et al., 2021). Interventions can either correct a current issue identified by monitoring twins or an expected future issue as forecasted by a predictive twin. Through simulations, intervention outcomes can be simulated to check their effectiveness. Cartas et al. (2022) mention that these types of systems should not only be used to understand the areas where new policies are needed but also to predict the impact of those policies by creating realistic KPIs on which they can be evaluated as mentioned in Section 2.3. An example from the healthcare sector for this, which can also apply to the city, is that of simulating different surgery scenarios (Expert 10). In this example, before surgery on a patient's heart is done, multiple scenarios will be simulated to determine the best possible way to operate on the patient.

Stage six implies that there is still a human decision-maker in the loop. CityOS in this stage only prescribes actions based on simulations of the predictive and prescriptive digital twins. This stage will be the final stage for most, if not all, strategic and tactical decisions If these types of decisions were to be taken autonomously, it would remove human accountability and explainability, which could lead to undermining political legitimacy within governments (Haraguci et al., 2024). Expert 10 also believes that these types of end decisions should only be taken by humans because of a need for human oversight.

Despite this, CityOS still achieves self-regulation with humans in the loop by providing the decision-maker with the data and evidence to make informed decisions. This is a great leap forward, as despite the recent advances in data capture and management, only 12% of city data is used for policymaking (Ruston et al., 2020).

CityOS at Stages 7 & 8: Autonomous Self-Regulation

In stages 7 and 8, CityOS has all the functionalities from previous stages but also uses autonomous reasoning and AI to make decisions independently and execute actions based on the predictive and prescriptive DTs. Moreover, CityOS will synchronize these actions back to the real world in real-time. Because of the reasons described in the previous section, this stage will mostly only affect operational-type decisions, as these require less human accountability.

To complete operational tasks autonomously, CityOS will have to utilize AI capabilities. AI needs to be used to draw conclusions from data and simulations of the system and to influence, optimize, or control the city without the need for human intervention (Talkhestani et al., 2019). By implementing machine learning algorithms on different models of the city, CityOS can continuously test what-if- scenarios, which help complete predictive maintenance and autonomously implement interventions in the city (Talkhestani et al., 2019).

This autonomous part of the system relies on the capabilities of the prescriptive, predictive, and monitoring Digital Twins. The autonomous component of the system uses these capabilities to identify inconsistencies or opportunities with the city’s ambitions and use simulations to find the optimal intervention. When an optimal intervention is found, it will be translated into actuator instructions, where the actuator will execute the intervention (Verdouw et al., 2021). By reaching this stage, CityOS will be able to learn from itself by measuring the effectiveness of the implemented intervention and using this information for future decisions.

An example of this could be dynamic mobility management, as described by Expert 2. They give the example of how the maximum speed on the roads in the city could be dynamically changed to avoid traffic congestion and the pollution it would cause. Expert 10 gives the same example but mentions that when giving AI control over stoplights or the current maximum speed limit, there need to be guardrails. These guardrails would serve a safety function, so for example, the maximum speed can only be changed within a predefined interval to secure the safety of the human population. Furthermore, Expert 5 believes that humans will still be in the loop in the end, as not everything can be actuated by technology, and sometimes implementing interventions will still require humans. Expert 3 mentions that autonomous self-regulation is not far in the future, as technically it is all possible. They pose that the main bottleneck for reaching this stage would be addressing the challenges surrounding privacy and ethical considerations when using AI.

To prevent this bottleneck, it is important to set guiding principles and know the current regulations around AI systems.

Guiding Principles for Artificial Intelligence in Cities

U4SSC created a list of guiding principles for the usage of artificial intelligence in cities. These principles pertain to general city aspects and apply to most cities. Table 9 shows these principles.

Guiding Principle	Description
Lawful	AI systems must identify all relevant and applicable laws and regulations and comply with them.
Privacy-Preserving	The use of information sets must comply with existing privacy regulations and laws set at the local or national level.
Fair and Inclusive	AI systems must be unbiased, non-discriminatory, and inclusive.
Explainable and Transparent	AI systems must be explainable and transparent.
Accountable	AI systems must have accountability built in.
Safe and Secure	AI systems have to be safe and secure.
High-performing and robust	AI systems must uphold acceptable performance levels.
Assessed for impact and sustainability	AI systems must be assessed and evaluated on their impact and consequences for the world.
Enabling human autonomy	Human autonomy over the AI system must be ensured.

Table 9 - Guiding Principles for Artificial Intelligence in Cities. Adopted from (U4SSC, 2024).

These guiding principles can be achieved through the following enablers, as noted by U4SSC (2024):

- Leadership, Governance, and Regulations
    - Government Leadership
    - Co-created policies
    - Data Governance to secure privacy
    - Information Security & Cybersecurity Principles
- AI Capacity and Skills Building
    - AI Education
    - AI capacity building in informal education
    - Monetary incentive to make AI-related education more accessible
    - Open Knowledge, Open Science, Open Learning Platforms
- City Systems Enablers: Public, Private & Inhabitants
    - R&D programs
    - Entrepreneurship programs
    - Investment
    - Raise Societal AI principles
- Technology platforms & Digital Infrastructure
    - Data accessibility

Current AI Regulations

As part of its digital strategy, the European Union has created the AI Act to ensure better conditions for the development and use of artificial intelligence (European Parliament, 2023). This regulation was made to make sure AI systems used in the EU are safe, transparent, non-discriminatory, and environmentally friendly. When creating CityOS, the following needs to be taken into account:

- CityOS cannot use cognitive behavioral manipulation of people or specific groups, social scoring systems, biometric identification and categorization of people, or real-time and remote biometric identification systems such as facial recognition.
- CityOS needs to be assessed because it could be seen as a high-risk AI system as it could manage and operate critical infrastructure.

Design Choices

In conclusion, CityOS can enable self-regulation in the city by providing decision-makers with real-time data and simulations through the use of predictive and prescriptive digital twins. For strategic and tactical decisions the decision maker will still be a human who decides whether to use the prescribed interventions or not. For most operational decisions they can be taken autonomously because they require less human accountability. However, it should be noted that for each specific use case, the governance board should consult both the Gemini principles and the AI guiding principles before approving.

From this section the following design choices were made:

- CityOS' decision-makers can be both human and non-human actors
- CityOS provides human decision-makers with data and simulations for evidence-informed decision-making
- CityOS' strategic and tactical decisions should have a human decision-maker
- CityOS' operational decisions can be taken autonomously
- CityOS' autonomous parts should have guardrails for safety
- CityOS should adhere to the AI principles set by U4SSC
- CityOS should adhere to AI regulations

In the following section, the data characteristics of CityOS will be discussed, as they play a critical role in ensuring self-regulation in the city.

5.2.2 Essential Data Characteristics in CityOS

With the main goal of the system being to enable self-regulation by unifying the entire city ecosystem to empower the city to manage and adjust its operations based on real-time data and simulations, the data plays a central role in its success. Using the right data, CityOS can model and simulate whole urban systems (Ruston McAleer et al., 2021). The dependency on data leads to some challenges, as a city should not just aim to collect as much data as possible, as this can bring serious ethical risks to the table (Raes, McAleer, et al., 2022). Initially, during the development of the conceptual model, it was only thought that data sources needed to be discussed, but during the expert interviews, it became evident that to get a clear overview, more data characteristics of the system needed to be touched upon. This is why, in this section, the four V's of data will be discussed. These are variety, volume, velocity, and veracity of data. First, the variety of data needed for the system will be discussed. Second, the volume of data in the system will be discussed. Third, the data velocity will be discussed. Fourth, the veracity of the data for the system will be discussed.

Variety

As Expert 5 rightly mentions, the city is a complex system that is very different from other industries like manufacturing. DTs in manufacturing are used to capture the entire product's production lifecycle from start to finish. This is impossible for most cities because most of them have existed for decades. This means there is already a rich history of heterogeneous data that can explain the reasons behind the city's current state. To make predictions for the future, data from the past also has to be utilized. To do this, CityOS needs to be able to handle both structured and unstructured data.

Structured data is often already organized and ordered in rows and columns. Structured data can be derived from existing data sets and can contain nominal, ordinal, discrete, or ratio data. Unstructured data is data that is not yet put into a structured data set; examples of this are text, images, videos, or sound. This unstructured data can then be transformed into structured data by, for example, sentiment analysis or feature extraction.

To build models for CityOS it would be smart to start with data that already exists as Expert 5 points out. An example of this would be using existing 3D data sets that contain data for most buildings. Expert 3 mentioned that their current DT project is mostly built from 3D BAG and BGT data which are national data sources updated by the cadaster. The expert advises that the system should use existing data wherever possible. Cartas et al (2022) mention the existence of the Common European Data Spaces, which can boost the sharing and re-use of data, which they believe will lead to achieving wider access to more open data.

CityOS would also greatly benefit from an open urban data platform that enables and combines data flows within and across both public and private city systems and infrastructure (Sheombar et al., 2020). CityOS can greatly benefit from such a platform, as it can handle most of the city's data already. However, it is not certain all cities will already have such a platform in place, as only about 30% of European cities currently have one operational (Sheombar et al., 2020). This means that CityOS should also be able to store and integrate its data in the scenario where such a platform does not yet exist.

In addition to existing data, CityOS should also collect data from sensor systems. There are different types of sensor systems, but the most important one is IoT sensors. IoT sensors are very useful because they can be connected to a network and provide a real-time data stream of what is happening at that moment. There are many different types of IoT sensors that collect different types of data. For example, they could collect temperature, humidity, images, videos, air quality, noise, etc. IoT sensors are a critical part of Digital Twins as they can measure almost everything and keep the model up-to-date.

Next to capturing the physical reality of a city, CityOS should also capture the social reality of a city. This can be done by harnessing its collective intelligence, which, as described in the introduction, is what makes each city unique. Kirwan & Fu (2020) describe it as: "The positive emergence of group wisdom from crowdsourcing intellectual capital." It is the combination of a city's collective knowledge, hard work, software, and technical experts. Which is needed to tackle the complex problems that require innovative thinking (Ruston McAleer et al., 2020). This can be done through active and passive citizen participation. Here, it is important to also gather data from hard-to-reach citizens from lower socioeconomic backgrounds to help remove as much bias from decision-making as possible (Ruston McAleer et al., 2021). Expert 8 also believes that, in addition to the physical reality, the social reality of the city should also be taken into account when simulating decision-making.

Citizens can actively participate by collecting data themselves using sensors or uploading data such as emotions to CityOS (Ruston McAleer et al., 2021). Additionally, citizens should be able to vote on interventions and present their interventions to the city. Expert 5 believes that the most valuable place for citizen participation is located at the end stage, where they could leave their opinions on different interventions or proposed policy changes.

In contrast to this expert 3, does think citizens can participate earlier in the process. He gives an example of a pilot in the city of Utrecht, where they give citizens devices that can be pressed when a citizen feels like a part of the city is too hot. This way, a citizen-generated heat map is built which can maybe differentiate from temperature sensors that measure heat. Here, it would mostly give data on perceived temperature which can be very useful when trying to locate the places in the city in need of cooling interventions. Additionally, citizens could actively participate by using a CityOS application to for example report when a streetlight is broken or when trash containers are full.

Next to this, citizens can participate passively through the use of agent-based modeling, where the system models the individual actions and interactions of the population of the city. This can be done with data from real-time footfall counters, environmental sensors, traffic detectors, and sentiment analysis from social platforms (Briks et al., 2020). Expert 10 believes that, if anonymized, population behavioral data could be very valuable for decision-making. Expert 8 mentions that they tried sentiment analysis on social media platforms but were unsuccessful because localization data was not available when analyzed. The expert would think that collecting sentiment analysis from city community boards would be more helpful, as this would be a place where only citizens can discuss topics regarding the city. Expert 5 notes that recent studies have been considering humans as sensors to feed UDTs with more data, but there are currently only a few pilots in place.

By using a variety of data sources, a more complete mirror of the city can be created to increase the quality and accuracy of the simulations.

Volume

The volume of data refers to the amount of data within the system. A UDT needs to be able to handle a large volume of heterogeneous data (Lei et al., 2021). This does not mean that CityOS should just collect and store as much data as possible. CityOS requires that its data be as efficient as possible. As the system grows, it should be flexible enough to scale with the increasing amount of newly generated data. Expert 5 mentions that digital twins are a way to create more data quality, data sharing, and data privacy, which breaks the cycle of every organization working alone and generating its own data. Every organization saves the same data instead of sharing it through a platform, which is inefficient. The expert, therefore, sees DTs as a way to collect and organize data to avoid duplication and create less data pollution in the ecosystem.

Expert 9 shared their approach to ensuring that the system can handle the volume of data. He recommends using a decentralized approach where data is not stored in one location but separated to spread the load and maintain flexibility.

Velocity

The velocity of data refers to the speed of data and its generation. In the ecosystem of CityOS, data flows at varying speeds. According to Experts 1, 3, 5, and 10, it is critical to see the difference between dynamic and static data within the city. An example of static data would be buildings that mostly change every 10 to 20 years. An example of dynamic data in the city would be traffic data, which can change every second. Keeping this difference in mind, CityOS should not collect data on all objects at the same rate. Furthermore, Expert 10 mentions that you should decide for each data source if you need new data continuously or if intervals are also enough to create accurate models. Expert 3 also highlights the potential dependence of actuality on legislation, such as the requirement for new buildings to register in the system within a specific timeframe. Therefore, it would not be smart to keep collecting data at all times. A better way to collect and update the system would be to only change the model when actual changes occur. Expert 3 gives an example of this from their projects, where they only collect data from temperature sensors above a certain threshold. This approach reduces the load on the system by preventing data pollution.

When data is collected, CityOS, depending on the use case, should be able to update its models in real-time. Traffic management is an example of a use case where CityOS needs to operate at a high speed. If a traffic management application like CityOS is not updated in real-time, this can cause major problems. The technology that can help with this is edge computing. When a part of a system is closer to the location where it is needed, it is called edge computing. So instead of processing and storing data on a far-off cloud server, edge computing brings the processing power closer to the operations (Kisters, 2023). By doing this, CityOS can significantly reduce its latency, which can be crucial in some use cases where the reaction speed of the system needs to be as high as possible.

Veracity

Data veracity refers to the quality of data. In this section, the quality of data needed in the system will be discussed. Expert 5 highlights that when simulating and optimizing the quality of the data, it has to be correct; otherwise, the output will be incorrect. Experts 4 and 6 see data quality as one of UDT's main challenges. Expert 4 believes that there needs to be a single point of truth in the system, while Experts 1 and 8 do not believe that this is the case, as in a city there can be a lot of different interpretations of data. Both parties are correct in some ways, as data from governments like building regulations should be a single point of truth, but for interpretations of simulation data, multiple truths can exist. But in both cases, the quality of the data must be assured.

The way that this can become challenging is when there is missing data, as Expert 5 points out in some cases, the system will need to fill in the missing data itself. There are different types of missing data. For example, observations can be missing, or some values in observations are missing. Selection bias may also occur when the data is not collected at random and does not represent the population. Furthermore, attrition can occur when some observations are less likely to be present due to time constraints. Instead of missing observations, the measurements may be faulty. An example of this can be when a sensor is malfunctioning. Additionally, Expert 5 mentions how some people also don't want to share data, which makes collecting data tricky. Expert 6 believes collecting high-quality data is a base condition for CityOS to work, which means working together with parties that can ensure the quality of their data. And also ensuring that when collecting data attention is paid to what data is collected and that it must be of use, instead of collecting everything without a goal.

To overcome data quality challenges cities should ensure they start with existing trusted data sources and then explore how to fill gaps. This means that having the skills to ensure data meets quality standards is also very important (Raes, McAleer, et al., 2022).

Next to data quality, UDTs also face data integration challenges as Expert 5 explains. These challenges stem from a mismatch in semantics, which can be solved mainly through the use of open standards.

Additionally, Experts 3, 4, and 6 see data privacy as a big challenge, referring to the fact that when combining specific datasets, sometimes they can be traced back to individuals. Expert 4 states that while data like the number of cars a community owns could be useful when deciding if there is a need for more parking spaces, it should never be possible to trace that information back to individuals. Expert 10 supports this and believes that all data collected should be directly anonymized so it is not traceable to individuals. To mitigate these ethical requirements, they always need to be applied when using new data sets. According to Russell McAleer et al. (2020), ethical requirements necessitate a clear public benefit, limited use, acknowledgment of data limitations, and a precautionary approach that prioritizes transparency, accountability, and openness in the acquisition, processing, storage, and use of data.

Expert 3 mentions a problem they have with their Digital Twin where they have discussions on what data should and should not be made public. An example of this is that they have a dataset where all the underground sewerage, water pipes, electricity connections, and internet connections are accessible to everyone. While they think this can be very useful, they also fear that it can be used maliciously. In the conversations with Experts 6 and 9, they both mention their fear of opening all data to everyone, specifically in the case that individuals could be targeted by, for example, insurance companies that might see that the air quality of a specific neighborhood is low and thus raise the insurance costs for the people living in those areas. According to Expert 1, this is why a governance board is so important to collaborate and discuss these grey areas, to decide what data combinations should be open and which shouldn't.

Design Choices

From the data characteristics, it is clear that CityOS should be able to collect heterogeneous data from both the physical reality and the social reality through different data collection methods. This data should be collected and stored as efficiently as possible to not waste system processing power. Moreover, it should only collect data when an entity changes to prevent data clutter. Additionally, CityOS should ensure that collected data is from trusted sources and of high quality. Lastly, it highlights the need to balance data openness with privacy to prevent misuse and protect individuals. From this section, the following design choices were made:

- CityOS should be able to integrate both structured and unstructured data
- CityOS should use existing data where possible
- CityOS should collect data from the physical realm of a city through sensors
- CityOS should collect the data from the social realm through passive and active citizen participation
- CityOS should be as efficient with its data as possible
- CityOS should only collect data when an entity changes
- CityOS should make use of edge computing for use cases where low latency is essential
- CityOS should ensure the quality of data collected is high
- CityOS' data should never be able to be traced back to an individual
- CityOS' governance board should decide on what data is open and what should be closed off to some to prevent misuse of data.

5.2.3 Design Choices: Self-Regulation

In summary, the self-regulation component shows to what extent CityOS enables self-regulation in the city. It also describes the different data characteristics of the system. In both design choices are made. Table 10 shows these choices.

Design Choice #	Description
25	CityOS' decision-makers can be both human and non-human actors
26	CityOS provides human decision-makers with data and simulations for evidence-informed decision-making
27	CityOS' strategic and tactical decisions should have a human decision-maker
28	CityOS' operational decisions can be taken autonomously
29	CityOS' autonomous parts should have guardrails for safety
30	CityOS should adhere to the AI principles set by U4SSC
31	CityOS should adhere to AI regulations
32	CityOS should be able to integrate both structured and unstructured data
33	CityOS should use existing data where possible
34	CityOS should collect data from the physical realm of a city through sensors
35	CityOS should collect the data from the social realm through passive and active citizen participation
36	CityOS should be efficient with its data
37	CityOS should only collect data when an entity changes
38	CityOS should make use of edge computing for use cases where low latency is essential
39	CityOS should ensure the quality of data collected is high
40	CityOS' data should never be able to be traced back to an individual
41	CityOS' governance board should decide on what data is open and what should be closed off to some to prevent misuse of data.

Table 10 - Design Choices Self-Regulation Component

5.3 Revised Design

By combining the knowledge from desk research and expert interviews, the initial design was refined into a revised design. This artifact shows a holistic approach to UDT design. The design shows a way for a city ecosystem to collaborate on a system that can benefit each stakeholder in their own way. Additionally, it shows how CityOS enables self-regulation in the city. Therefore, this part describes the mediator variable of this paper.

5.3.1 Design Choices CityOS

The revised design incorporates all the design choices from the design cycle. Table 11 shows all design choices in one table. These design choices will be incorporated into the revised design. However, it should be noted that some choices cannot be visualized.

Design Choice #	Description
1	CityOS should be seen as the cerebral cortex of the city
2	CityOS is based on digital twin technology
3	CityOS enables the use of imaginary, monitoring, predictive, prescriptive, autonomous, and recollection digital twins
4	CityOS should monitor the different states of the city autonomously to find inconsistencies with the city's ambitions
5	CityOS should capture both the physical realm and the human realm of the city
6	CityOS follows smart city principles to establish transparent, fair, and inclusive mechanisms
7	CityOS' core objective is to unify the city ecosystem to empower cities to manage and adjust their operations in real-time based on data and simulations
8	CityOS focuses on one city's ecosystem and is bounded by the city limits
9	CityOS' main stakeholder groups are public organizations, citizens & communities, academia, and private organizations
10	CityOS' architectural guiding principle is 'form follows function' to reflect the dynamic flow of the city
11	CityOS should have the capability to integrate data, generate models, simulate and actuate interventions, utilize open standards, and synchronize the digital twin with the real-world

12	CityOS should be interoperable, compatible, scalable, maintainable, reconfigurable, extensible, fidelity, efficient
13	CityOS should adopt a hybrid pattern between layered, SOA, component-based, and federated learning to ensure scalability, maintainability, flexibility, interoperability, and privacy-compliant
14	CityOS should adopt a centralized, decentralized, and distributed hybrid topology to support the complex system and distribute system load.
15	CityOS should be built on a public stack if possible to increase transparency, democracy, equality, and citizen participation in the system.
16	CityOS is to be a living lab allowing for co-creation and co-development of the system
17	CityOS should be developed openly and be modular to prevent vendor lock-in
18	CityOS should offer base models and functionalities to all city ecosystem stakeholders
19	CityOS should be accessible to all city ecosystem stakeholder groups to promote inclusivity
20	CityOS' stakeholders should be able to create value by using the system for both public and private use cases
21	CityOS should adopt a governance board consisting of representatives of all stakeholder groups to promote cooperation and knowledge-sharing
22	CityOS' governance board must ensure that CityOS is operated ethically and responsibly
23	CityOS' governance board should use guiding principles like purpose, trust, and function to decide on use cases of the system
24	CityOS should use open standards throughout the system to ensure interoperability
25	CityOS' decision-makers can be both human and non-human actors
26	CityOS provides human decision-makers with data and simulations for evidence-informed decision-making

27	CityOS' strategic and tactical decisions should have a human decision-maker
28	CityOS' operational decisions can be taken autonomously
29	CityOS' autonomous parts should have guardrails for safety
30	CityOS should adhere to the AI principles set by U4SSC
31	CityOS should adhere to AI regulations
32	CityOS should be able to integrate both structured and unstructured data
33	CityOS should use existing data where possible
34	CityOS should collect data from the physical realm of a city through sensors
35	CityOS should collect the data from the social realm through passive and active citizen participation
36	CityOS should be efficient with its data
37	CityOS should only collect data when an entity changes
38	CityOS should make use of edge computing for use cases where low latency is essential
39	CityOS should ensure the quality of data collected is high
40	CityOS' data should never be able to be traced back to an individual
41	CityOS' governance board should decide on what data is open and what should be closed off to some to prevent misuse of data.

Table 11 - Design Choices CityOS

5.3.2 Revision Considerations

The main considerations for the changes from the initial design stem from the expert interviews. The experts' evaluation of the initial design revealed some unclear or missing elements. These were mostly the clarity of the ecosystem-driven components and the self-regulation components. To refine the design, changes were made to show:

- What parts of the city are included in the models;
- The different types of data acquisition;
- That both dynamic and static data are collected;
- How future states are created based on historical and current states;
- The decision-maker can be either human or nonhuman;
- How the prescriptive digital twin works;

- How the different use cases fit in the design;
- The governance board and its guiding principles;
- The system uses open standards throughout.

5.3.3 CityOS Description

The revised design (Fig. 12) shows the city as its foundation, representing both the physical domain—comprised of the physical infrastructure, nature, landscape, and environment—and the human realm, encompassing the society of a city with its ecosystem stakeholders.

Data acquisition methods such as sensors and sentiment analysis capture the current state of both the physical domain and the human realm. This data is collected either in real-time or at intervals, depending on which is needed. Once gathered, this data is combined with existing and external data to form a data platform.

Using this data, DTs of the city can be constructed, enabling the monitoring of both the city's current and historical states. Combining these states with external data can be used to forecast potential future city-states.

These three states—past, present, and future—are continuously monitored, and the status is relayed to the decision-makers. The decision-maker can be both human and non-human, depending on the nature of the use case. Strategic and tactical decisions necessitate more human oversight, whereas operational decisions can be managed autonomously by an AI or computer model.

Based on continuous monitoring and self-diagnosis, decision-makers can propose interventions for the city. These proposals will be evaluated by the prescriptive digital twin, which simulates the impact and effectiveness of the intervention on the city's current state to predict future outcomes. The decision-makers then assess whether to implement the proposed intervention or explore alternative options. Should an intervention be approved, policies can be changed or instructions can be sent to actuators who will implement the changes in the city. This in turn will alter the real-world state of the city and initiate a new cycle of monitoring and evaluation to test the actual effectiveness of the intervention, thereby enabling self-learning.

The specific features available to users can vary depending on the use case and the system's user. Not all users of the system will have the authority to modify city policies or control actuators. A governance board, with representatives from the four stakeholder groups, determines these permissions. Additionally, they decide on guardrails for the system and ensure that CityOS is operated ethically and responsibly. The governance board's decisions will be informed by the city's ambitions, UN SDGs, and AI regulations and guided by the Gemini, smart city, and AI principles. Furthermore, to ensure the system's interoperability, all data flows and components must use open standards.

In conclusion, CityOS' design shows a high-level overview of a system that can be used for managing and operating the city through real-time data and simulations, enabling self-regulation. It highlights the use of both the physical and human realms as data sources for accurate simulations. Moreover, it shows the ecosystem-driven nature of the city, where the system is both used and governed by the city's ecosystem stakeholders. CityOS allows for informed human decision-making and autonomous system actions, helping the city's process toward urban homeostasis.

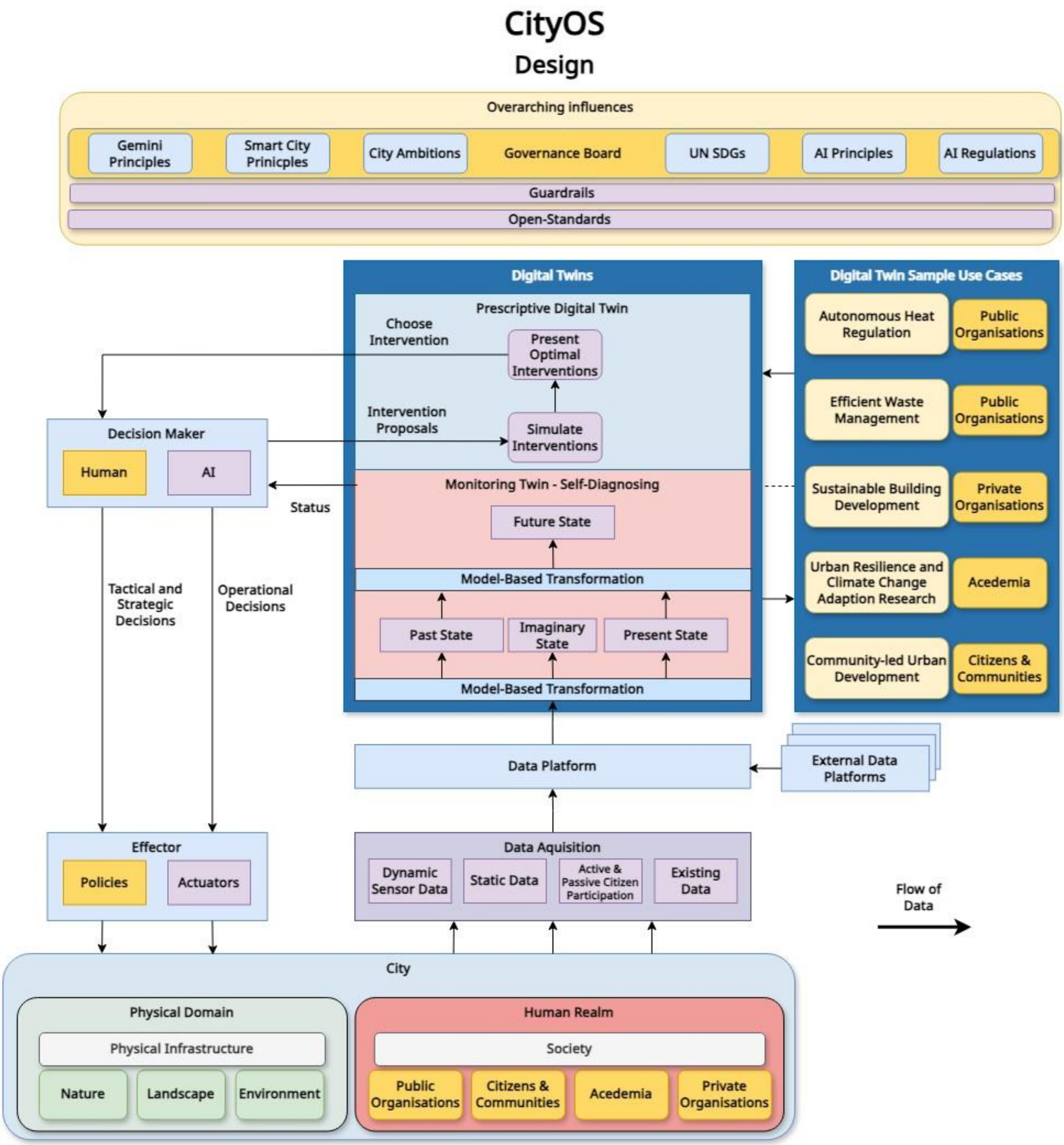

Figure 12 - Revised Design of CityOS

6 Discussion

In this section, the research will be discussed. First, the DSR cycles and methodology will be discussed and reflected on. Second, the propositions will be analyzed and discussed. Third, a revised version of the conceptual model will be developed and discussed. Lastly, concepts that fell out of the scope of this research but still needed to be mentioned will be discussed.

6.1 Design Study Research

This paper followed the Design Study Research approach as outlined by Henver et al. (2004) and von Brocke et al. (2020). The study aimed to explore the potential of urban digital twins to enable self-regulation in cities by adopting a holistic approach to their design. To conduct the DSR methodology, the research underwent three cycles: relevance, rigor, and design.

In the relevance cycle, the paper identified the need for cities to find a balance between nature, humankind, and technology, and it was found that DT technology could be utilized to achieve this.

In the rigor cycle, a knowledge base was created. First, a review was done of academic smart city and digital twin literature. The review revealed a gap in the literature, where it was found that current applications of UDTs are fragmented and focused on specific city systems or domains without considering the city as an interconnected ecosystem. This led to the creation of a conceptual model and the following propositions:

- Proposition 1: The design of a holistic UDT is comprised of meta-architecture, ecosystem, and self-regulation components.
- Proposition 2: The meta-architecture sets guidelines for the components of a holistic UDT design.
- Proposition 3: The design of a holistic UDT influences the capability of a UDT to enable a city to achieve self-regulation.

These propositions led to the second part of developing the knowledge base, where desk research was conducted, consulting academic as well as practical literature and reports to start the design cycle and create the meta-architecture and an initial version of the design. This initial design was evaluated and refined through additional desk research and most notably expert interviews. Expert interviews were also used to further develop the components of the design. This resulted in 41 design choices which were used to make a revised version of CityOS' design.

Rigor of Literature

Applying the DSR methodology required extensive research on the topic of smart cities and digital twins. To ensure the quality and relevancy of consulted papers it was made sure to mostly use highly cited and recent papers. For some parts of this research, it was harder to find relevant papers as most literature on digital twins is quite underdeveloped when placed in an urban setting, comparing this to other settings like manufacturing or agriculture which are more mature. This was most notable in the self-regulation and autonomous parts of the research. These parts required consulting papers that describe digital twins in other settings to develop those parts for the urban setting. Non-academic literature was found to be more mature so this could be used more effectively in the design process. For the non-academic literature, it was also ensured to only collect data from medium to large and known organizations to maintain the quality of the sources.

Rigor of Expert Interviews

The results of the expert interview change per expert. Some experts have more knowledge on the topic than others. This resulted in some experts having more input on the design and topic than others. A suggestion for future research would be to conduct interviews in person when possible, as this could positively increase the ease of explaining the topic, and make the design process more engaging.

Furthermore, it was found that most of the opinions from the experts corresponded with those from academic literature. This was most notable while designing the ecosystem-driven component. Here most experts promoted the smart city principles as mentioned in section 2.1. This was unexpected as public organizations are in most cases seen as slow-moving entities with a lot of bureaucracy. While this may still be true it should be noted that the people leading the digital transition are open to change.

Design Cycle

The design cycle started as soon as the desk research part of the rigor cycle started. This meant that the design process occurred parallel to part of the knowledge base creation. This was done because of the limited time available for the research. This also caused the design cycle to be more iterative as the design was edited whenever new data was collected to refine the design. It was chosen to only show an initial design and a revised design to limit the size of this already extensive paper.

Furthermore, showing all 41 design choices in one design is not that easy as some design choices are not easily visualized. To decide on the structure of the design, publications like Verdouw et al. (2020) and Sheombar et al. (2020) were consulted to learn ways to visualize a complicated system.

Additionally, it should be noted that the revised design could still be iterated and refined with more time and resources. This means that the design is by no means final, and should not be treated like one. The design is a great starting point for future initiatives to refine and improve on.

Finally, applying the DSR methodology proved to be a great method for developing a design that can be used both by academics and non-academics to solve real-world problems. The methodology provides clear guidelines for an iterative design process which helps create valid research results. However, it is important to know that the methodology requires a substantial time commitment as it takes time to develop an artifact through an iterative process.

The CityOS Design

The results derived from the rigor and design cycles resulted in the design of a holistic urban digital twin. This design was guided by the ideas of Kirwan and Fu (2020) to create a system that harnesses the collective intelligence of a city to achieve homeostasis in the city. It should be noted that the system designed in this paper is unlikely to be the only way to achieve homeostasis in the city. Moreover, just implementing this system in the city will not automatically result in homeostasis in the city. Because the system is designed to be ecosystem-driven, its success is also dependent on the entire ecosystem coming together. While this system would make it easier for the ecosystem to collaborate it still relies on the willingness of the different parties in the city to come together.

Additionally, the design of CityOS is reliant on data and computer processing power to enable all simulations to be accurate. This also implies the need for all stakeholders to work together to share data and divide the processing load to be able to run the system effectively. This requires a mentality shift of the whole ecosystem.

Moreover, because the system would use AI to autonomously manage operations, it should follow strict AI guidelines and regulations to ensure the safety of the population of the city. The same has to be mentioned for privacy. As mentioned before it is crucial that the system is fair and inclusive and does not discriminate individuals or groups in any way or form.

Finally, it should be noted that there are many ways for a city to become smart. This study presents one way, but it should not be seen as the only way for a city to become smart and sustainable.

6.2 Analysis of Propositions

In this section, the propositions will be analyzed and discussed to determine if they should be accepted or rejected.

Proposition 1: *The design of a holistic UDT is comprised of meta-architecture, ecosystems, and self-regulation components.*

The first proposition states that the design of a holistic urban digital twin is comprised of meta-architecture and the components of ecosystems-driven and self-regulation. During the DSR cycles, it was found that meta-architecture could provide a high-level overview of the system. Therefore, a meta-architecture was created and used to communicate the proposed system to both technical and non-technical experts.

Furthermore, during the desk research and expert interviews. The most recurring themes were those that either fit in the meta-architecture, ecosystem-driven, or self-regulation parts. For the ecosystem, the most relevant themes found were transparency, open standards, governance, and use cases for the system. Almost all experts mentioned it would be good to avoid vendor lock by open development and modularization. However, they did mention a downside to this approach being the lack of one-party responsibility to implement new features or to act as a helpdesk when issues arise. Moreover, the theme of open standards was one of the most recurring themes and was highlighted as one of the key drivers for success.

During the development of the self-regulation component, it was discovered how underdeveloped urban digital twins currently are in the real world. Talking to the experts who work on pilot UDTs in their city, it became clear that while they do have a 3D version of the city, this is not used to inform decisions yet. In contrast, UDT literature is more mature as it highlights autonomous functions and prescriptive modeling as one of the main features.

Based on the research and design processes, the suggested components ensure the most important parts of the UDT design are covered. However, additional components could make the design more extensive and clearer. Additional components that go more in-depth on the technical side like how models should be built and simulations should be run could be a fine addition but are out of scope for this study. Nevertheless, the results from the DSR cycles corroborate the necessity of the designed components. Therefore, proposition 1 is accepted.

Proposition 2: *The meta-architecture sets guidelines for the components of a holistic UDT design.*

The second proposition states that the meta-architecture sets the guidelines for the components of the holistic urban digital twin design. The findings of this study support this proposition by showing that a well-defined meta-architecture is crucial in guiding the design of the components and the overall design of the system.

First, the meta-architecture provided a high-level overview showing the proposed systems' overarching vision. By specifying the parts of the meta-architecture, it can be used to align stakeholders. This alignment is vital for the design process to get everyone involved and on the same page.

Second, the architectural strategy provides a clear approach to design by addressing both guiding principles and necessary system capabilities. Furthermore, it informs system architects of the best patterns to adopt during the system's creation.

Without a meta-architecture, the design process risks becoming directionless. The lack of a clear vision can hinder effective communication with stakeholders. Additionally, it was found that by first defining the meta-architecture the design cycle for the components was easy as it gave a clear overview of the system and its specifications. By creating a high-level overview of the system, the meta-architecture sets the guidelines for the design of the components. Therefore, proposition 2 is accepted.

Proposition 3: *The design of a holistic UDT influences the capability of a UDT to enable a city to achieve self-regulation.*

The third proposition states that the design of a holistic UDT influences the capability of a UDT to enable a city to achieve self-regulation. This paper's findings support this proposition by highlighting that a UDT design, guided by a meta-architecture can enhance the city's ability to manage and adapt its operations in real-time based on data and simulations.

CityOS' design, including the meta-architecture, ecosystem-driven, and self-regulation components, shows how the city can increase its ability to self-regulate. It also shows how CityOS can dynamically monitor and directly respond when issues arise.

One of the main findings is that CityOS supports evidence-informed decision-making in strategic, tactical, and operational decision scenarios. By combining the present and historical states of the city, the future states of the city can be forecasted. By monitoring these states, insights can be gained, which can be used by the city to anticipate and mitigate issues proactively. Moreover, the monitoring function can also enable CityOS to self-diagnose based on predefined city ambitions like KPIs or sustainable development goals. By self-diagnosing, CityOS can also autonomously find optimal interventions through what-if simulations. Therefore, self-regulation can be initiated by both city ecosystem stakeholders and the system itself.

By not only integrating the physical aspects of the city but also using inputs from public organizations, private entities, academia, and citizens, CityOS creates a close mirror of the city. This ecosystem-driven approach increases the system's resilience as it uses insights and feedback from the entire city ecosystem, which results in an increased accuracy in predictions.

The study also revealed that, while CityOS could manage all city decisions autonomously, it suggests only making operational decisions autonomously. This is because higher-level strategic and tactical decisions need more human oversight and accountability to ensure explainability and prevent undermining the political legitimacy of the government. Autonomous self-regulation will be most effective in operational areas such as waste management, traffic control, and environmental monitoring, where an autonomous and direct response is most needed.

However, the study also highlights some challenges when implementing a self-regulating CityOS. Data availability and quality are crucial for the system, as it needs comprehensive, high-quality, and real-time data to function. Moreover, the integration of AI must be done following guiding principles and regulations to ensure the system's transparency, fairness, and accountability. Additionally, the study highlights that finding a balance between data openness and privacy is vital to preventing the misuse of personal and sensitive data. Furthermore, as interoperability remains a challenge, the use of open standards is crucial. Open standards are essential in ensuring that data can be seamlessly exchanged between all modules.

In conclusion, proposition 3 is supported by this paper's findings. The design of CityOS influences the self-regulation of a city by enhancing operations, enabling evidence-informed decision-making, and integrating the collective intelligence of the city's stakeholders. While there are still challenges, specifically in the realm of data management and interoperability, the potential benefits of the proposed system are substantial. Therefore, proposition 3 is **accepted**.

6.3 Revised Conceptual Model

In this section, the conceptual model will be refined per the findings of this paper. The initial conceptual model was created based on the literature review. During the rigor and design cycle, a few additional parts were discovered that would change the conceptual model slightly. Figure 13 displays the revised version of the conceptual model.

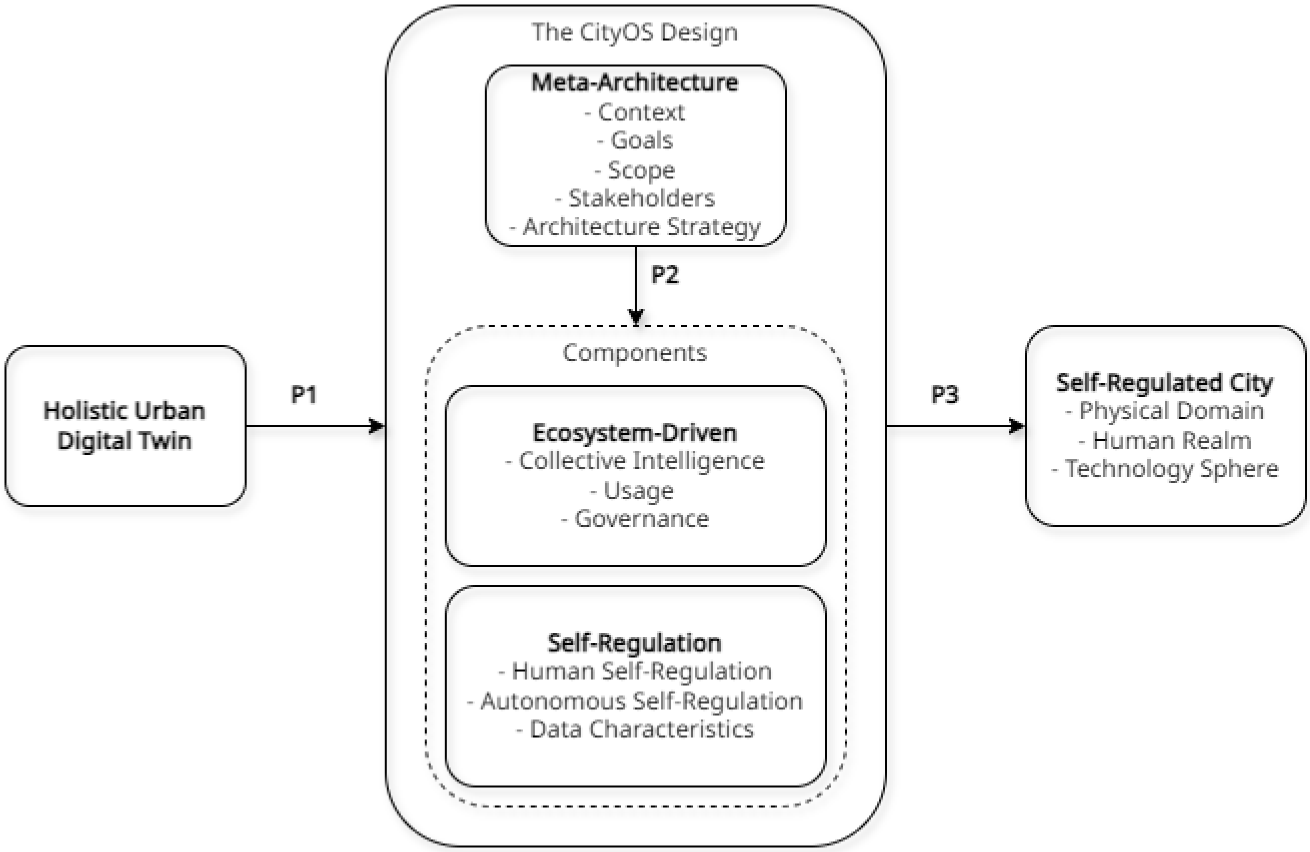

Figure 13 - Revised Conceptual Model

This revised version of the conceptual model incorporates several additions and modifications based on this study's findings. First, the mediator variable gets the name of CityOS to reflect the name of the created design in this study. The second modification is within the variable “Meta-Architecture” where the sub-variable “Stakeholders” has been included. Stakeholders were identified as a vital part of a high-level system overview. Including stakeholders is critical because their nature can significantly influence the design of a system. Therefore, including stakeholders in the meta-architecture ensures an understanding of their role and impact within the system design.

Furthermore, in the variable “Self-Regulation,” several adjustments were made based on the research findings. Initially, only the sub-variables “Autonomous” and “Data Sources” were added. However, during the rigor and design cycles, it became clear that there is a notable difference between human self-regulation and autonomous self-regulation. This difference became clear when discussing the different types of decisions the system can or should make. Therefore, the revised model shows the distinction between the two. Additionally, it was found that only referring to “Data Sources” was insufficient in capturing the complexity of data within the system design. Therefore the sub-variable was changed to “Data Characteristics” to create a better representation of the data-related aspects of the system.

Lastly, the sub-variables of the "Self-Regulated City" variable were changed to better align with the terminology used in the design process. It was found that these terms more accurately reflect the different domains of the city.

6.4 Conceptual Limitations

This section describes the concepts that are out of scope for this research but which were found to be insightful for the topic. These insights highlight benefits, challenges, and recommendations regarding CityOS.

In addition to the previously discussed benefits, CityOS can bring benefits in long-term cost savings. According to Expert 8, UDTs can save cities billions of euros. These savings stem from first-time-right designs, which avoid the expense of having to modify interventions later. CityOS can reduce costs by proactively predicting issues, enabling the city to solve problems preemptively. Moreover, by adopting an ecosystem-driven approach, CityOS contributes to creating a sense of sharing, transparency, equality, citizen participation, innovation, democracy, and openness in the city.

While CityOS, when fully implemented, can yield significant benefits for the city ecosystem, Expert 8 suggests that patience is key. They advocate for the gradual integration of such a system, as it needs to evolve and grow over time. Expert 5 believes that integrating CityOS through pilots and during the development of new city districts would be an effective implementation strategy. Expert 3 added that a significant technological push from the EU is needed to kickstart development, as currently "only a small group of people understand what DTs can bring to the table."

In addition to these benefits, there are also some challenges CityOS faces. The initial implementation and development of the system may be costly. Experts 3 and 5 mention that: "we are currently far from a true digital twin," saying that the adoption of the system may be the biggest hurdle.

Finally, Experts 3, 5, and 8 believe that convincing people, departments, and organizations that using DT technology is the new approach to decision-making. Expert 8 said," Adopting a tool such as CityOS might be scary because organizations have had their own way of working for a long time, but combining data from different sectors could be very beneficial for them."

7 Conclusions and Implications

7.1 Main Conclusion

This paper addressed the concept of self-regulation in cities by proposing a holistic approach to urban digital twin design. It was found that cities, just like living organisms, are dynamic and complex systems that need to be able to regulate their operations in real-time to respond to all the city functions in harmony. It was found that digital twin technology could help achieve this objective. Additionally, it was also found that current applications of urban digital twins are fragmented and do not encompass the whole city ecosystem. Therefore, this paper explored how a holistic approach to urban digital twin design could enable the self-regulation of a city. Using the Design Science Research methodology, this paper presents a high-level design for CityOS a holistic approach to urban digital twins. The design is created based on 41 design choices which were gathered through academic literature, desk research, and expert interviews. The findings suggest that a holistic approach to urban digital twin design enables the self-regulation of a smart city by unifying all city systems into an ecosystem-driven platform that allows for the real-time adaption and management of operations based on data and simulations. The latter leads to answering the main research question:

How does a holistic approach to urban digital twin design enable the self-regulation of a smart city?

Firstly, this paper presents a meta-architecture that serves as a high-level blueprint, providing the context, goals, scope, stakeholders, and architectural strategy of CityOS. It shows that CityOS should be seen as the cerebral cortex of a city serving as an operating system managing and adapting its operations based on real-time data and simulations. It also showed that CityOS' main goal is to achieve urban homeostasis by unifying the whole city ecosystem. Additionally, it showed its main stakeholders are citizens & communities, public organizations, academia, and private organizations. Furthermore, the meta-architecture shows the architectural strategy by describing its proposed capabilities, attributes, patterns, and technological considerations. This high-level overview ensures that all design efforts are aligned and can be communicated with both technical and non-technical stakeholders.

Secondly, the paper presents the ecosystem-driven component of the design which states that the system should be a collaborative, open, and modular system that harnesses the collective intelligence of the city's ecosystem. This is achieved, first, through creating the system as a living lab allowing for co-development and co-creation. Second, by making the system accessible to all stakeholders to allow for the development of unique use cases.

Third, by decentralizing governance through a governance board with representatives from all stakeholder groups to ensure that the system is used responsibly.

Thirdly, the paper presents the self-regulation component of the design which shows to what extent self-regulation can be achieved and discusses the data characteristics of the system. It shows how CityOS can enable self-regulation in the city by providing decision-makers with real-time data and simulations through the use of predictive and prescriptive digital twins. It suggests that in strategic and tactical decisions human oversight is still needed. But that for most operational decisions they can be taken autonomously because they require less human accountability. Furthermore, it shows how CityOS is capable of self-diagnosis through monitoring the city based on the city's ambitions.

The data characteristics show that CityOS should be able to collect heterogeneous data from both the physical reality and the social reality through different data collection methods. It shows that data should be collected and stored as efficiently as possible to not waste system processing power. Moreover, it shows that the system should only collect data when an entity changes to prevent data clutter. Additionally, it shows that CityOS should ensure that collected data is from trusted sources and of high quality. Lastly, it highlights the need to balance data openness with privacy to prevent misuse and protect individuals.

This research concludes that a holistic approach to urban digital twin design enables the self-regulation of a smart city by unifying all city systems into an ecosystem-driven platform that allows for the real-time adaption and management of operations based on data and simulations.

7.2 Theoretical Contributions and Implications

This paper makes several theoretical contributions to the field of urban digital twins and smart cities.

First, this study presents an artifact that combines UDT technology with the concept of self-regulation, which provides a novel framework for understanding how a city can manage its operations in real-time. This adds to theoretical discourse by showing how digital twin technology could be used in a complex urban environment. It provides a base for future research exploring how cities can use technology to become more smart and sustainable.

Second, by advocating for a holistic approach to UDT design, the study shows the need for considering the city as a complex interconnected ecosystem, rather than the collection of separate parts. This could encourage other researchers to adopt this view of the city when designing new systems for the city. This also pushes for the city to become more collaborative and inclusive.

Third, this study presents a meta-architecture that can be used as a reference point for future studies and projects. Which could improve project alignment between technical and non-technical stakeholders.

Fourth, this paper highlights the role of collective intelligence and collaboration in the success of a city. This ecosystem-driven approach provides a template for developing more inclusive and democratic solutions within cities or even countries.

Lastly, the findings of the paper also offer a foundation for future academic research in the domain of urban digital twins. Researchers can use the insights gained from this paper as a starting point for further exploration or as part of a knowledge base for their projects.

7.3 Managerial Implications

The paper provides initiators from all city ecosystem stakeholder groups with practical guidance on creating and implementing a self-regulating CityOS. The design highlights the importance of stakeholder engagement, the adoption of open standards, and the integration of high-quality data.

CityOS unifies the whole city ecosystem to create a sense of sharing, transparency, equality, social participation, innovation, and openness. This opens up different business cases for not only municipalities but also for private and other public organizations to start collaborating with the ecosystem. The system is seen as a living lab where the ecosystem can come together to co-create and co-develop new solutions to enhance and create value for the city.

The findings of this paper suggest that while CityOS can bring many benefits to a city, it must be noted that adopting and developing such a system takes time and resources. It should not be expected that a fully-fledged CityOS will be operational within 5 years. Initiators should take into account that a system like the one presented needs planning, pilot development and testing, scaling, integration, and adoption while adhering to privacy and AI regulations.

While the goal of the system is to unify and to be used for positive and good purposes, the implementation of a powerful system such as CityOS can also be used for "bad" purposes. If a system like the one described in this paper does not carefully follow regulations, ethical principles, and security standards, it could bring forward the opposite of what the system was made for, such as a reduction of public safety, privacy, and human autonomy. Therefore, following regulations and thinking about the ethical implications of the system should be the main priority. Adopting such a system should focus on informed consent for its citizens when collecting data from public spaces. Additionally, while the CityOS is partly designed as an autonomous system it is vital for humans to still keep oversight and the ability to intervene if needed.

7.4 Generalizability and Limitations

When conducting research, it is important to evaluate the generalizability and limitations of the research. This assessment of the paper is crucial to understanding the scope of the findings and their applicability to other settings.

This research was conducted in the setting of a master thesis, which means the research was conducted in a limited time frame of 20 weeks by a single student under the supervision of two experienced researchers. Additionally, the research is not funded and thus has no budget. Only resources accessible for free as a student at Erasmus University Rotterdam were used. This means that some academic literature could not be accessed due to a paywall.

Furthermore, this also means the sourcing process for experts was limited to the extended network of the author. As a result, the majority of the experts were from Europe, specifically from the Benelux. Potential candidates for expert positions outside of this region were contacted but were not available for an interview. Moreover, time constraints and expert availability limited the number of experts interviewed to just ten. Therefore, it can be concluded that the findings of this paper are generalizable to most cities with similar regulatory and technological landscapes.

Another limitation stemming from the limited time, resources, and expertise is the lack of a comprehensive technical analysis of the design and the potential for a small-scale pilot study, which could have strengthened the conclusions. Moreover, the present study is an explorative design study and does not explicitly compare the difference between a holistic urban digital twin and a "non" holistic urban digital twin. Its goal was to explore how a holistic approach could enable the city to become self-regulated.

7.5 Directions for Future Research

This paper creates a starting point for a plethora of future research opportunities.

First, this paper can serve as the foundation for research into architecting small-scale pilots to evaluate CityOS' design in the real world which could strengthen the conclusions of this study.

Second, with this design being mostly technology-agnostic, more technical research must be conducted to find out the best ways to distribute the computational power of the system, securely store data, and integrate data.

Third, the design could be evaluated and iterated by inviting more experts to speak on the design. This can lead to the design becoming more refined.

Fourth, this paper can initiate research into specific components, such as how to set up the governance board, what open standards should be used, or how to set up business models for the system.

Fifth, further research could be done to identify the costs, financial benefits, and business models of CityOS. This would help convince stakeholders and investors to allocate more resources to the development and research of holistic urban digital twins.

Sixth, a comparative study can be done to compare the difference in efficacy in self-regulation between a holistic urban digital twin and fragmented urban digital twins.

Finally, due to the explorative nature of this research, many different design changes could be investigated as knowledge about smart cities and digital twin technologies evolves and matures.

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9 Appendices

Appendix I – Different versions of the triple helix of a city

Pillar 1	Pillar 2	Pillar 3	Source
Social	Environmental	Economic	-
Social	Environmental	Governance	UNGC, 2004
People	Planet	Profit	(Elkington, 1994)
People	Planet	Prosperity	(United Nations, 2002)
Society & Culture	Environment	Economy	(U4SSC, 2017)
Humankind	Nature	Technology	(Kirwan & Fu, 2020)
Human	Physical	Technology	(Kirwan & Fu, 2020)
Social	Physical	Digital	(Gemeente Rotterdam, n.d.)

Appendix II – Smart City Domains

Smart governance refers to the use of a city network to enable political efficiency, social and cultural development, and urban development (Albino et al., 2015). Kirwan and Fu (2020) highlight the role of citizen participation, transparency, and open data in smart governance. This approach would allow for more citizen participation and more transparency in the decision-making process of the government. Smart governance should lead to inclusiveness (Kirwan & Fu, 2020).

Smart people refer to the enlightenment of society and culture in a city (Kirwan & Fu, 2020). In smart cities, education should be accessible to everyone as well-educated citizens are the main driving force behind the collective intelligence of a city (Anthopolos, 2017; Kirwan & Fu, 2020). Smart cities aim to increase the quality of life for their citizens and foster an environment for citizen participation (Chourabi et al., 2012).

Smart mobility refers to the application of technology to improve mobility in a city (Kirwan & Fu, 2020). Smart mobility emphasizes local and international accessibility and the development of sustainable transport systems (Giffinger et al., 2007).

Smart living refers to how technology enhances people's lives by making them more efficient, automated, and productive (Kirwan & Fu, 2020). It is about innovating to improve the quality of life in cities (Anthopoulos, 2017). The main aspects of smart living are health, well-being, safety, housing quality, and social cohesion (Giffinger et al., 2007).

Smart environment refers to how technology is used to protect and manage natural resources. The main themes of Smart Environment are resource consumption optimization, renewable energy, biomimicry, and carbon neutrality (Anthopoulos, 2017; Kirwan & Fu, 2020).

Smart economy refers to the application of technology to enhance business development, drive economic competitiveness, and increase productivity (Anthopoulos, 2017). A smart economy includes elements of entrepreneurship, innovation, circular economy principles, and a universal basic income to create prosperity for all citizens (Kirwan & Fu, 2020).

Appendix III – List of KPIs for Smart Sustainable Cities

Dimension	Sub -Dimension	Category	KPI
Economy	ICT	ICT Infrastructure	Household Internet Access
			Fixed Broadband Subscriptions
			Wireless Broadband Subscriptions
			Wireless Broadband Coverage
			Availability of WIFI in Public Areas
		Water and Sanitation	Smart Water Meters
			Water Supply ICT Monitoring
		Drainage	Drainage / Storm Water System ICT Monitoring
		Electricity Supply	Smart Electricity Meters
			Electricity Supply ICT Monitoring
			Demand Response Penetration
		Transport	Dynamic Public Transport Information
			Traffic Monitoring
			Intersection Control
		Public Sector	Open data
			E-Government
			Public Sector e-procurement
	Productivity	Innovation	R&D Expenditure
			Patents
			Small and Medium-Sized Enterprises
		Employment	Unemployment Rate

			Youth Unemployment Rate
			Tourism Sector Employment
			ICT Sector Employment
Economy	Infrastructure	Water and Sanitation	Basic Water Supply
			Potable Water Supply
			Water Supply Loss
			Wastewater Collection
			Household Sanitation
		Waste	Solid Waste Collection
		Electricity Supply	Electricity System Outage Frequency
			Electricity System Outage Time
			Access to Electricity
		Transport	Public Transport Network
			Public Transport Network Convenience
			Bicycle Network
			Transportation Mode Share
			Travel Time Index
			Shared Bicycles
			Shared Vehicles
			Low-Carbon Emission Passenger Vehicles
		Buildings	Public Building Sustainability
			Integrated Building Management Systems in Public Buildings
		Urban Planning	Pedestrian infrastructure
			Urban Development and Spatial Planning
Environment	Environment	Air quality	Air pollution
			GHG Emissions
		Water and Sanitation	Drinking Water Quality
			Water Consumption
			Freshwater Consumption
			Wastewater Treatment
		Waste	Solid Waste Treatment
			EMF Exposure

		Environmental Quality	Noise Exposure
		Public Space and Nature	Green Areas
			Green Area Accessibility
			Protected Natural Areas
			Recreational Facilities
	Energy	Energy	Renewable Energy Consumption
			Electricity Consumption
			Residential Thermal Energy Consumption
			Public Building Energy Consumption
Dimension	Sub -Dimension	Category	KPI
Society and Culture	Education, Health and Culture	Education	Student ICT Access
			School Enrolment
			Higher Education Degrees
			Adult Literacy
		Health	Electronic Health Records
			Life Expectancy
			Maternal Mortality Rate
			Physicians
			In-Patient Hospital Beds
			Health Insurance / Public Health Coverage
		Culture	Cultural Expenditure
			Cultural Infrastructure
	Safety, Housing and Social Inclusion	Housing	Informal Settlements
			Housing Expenditure
		Social inclusion	Gender Income Equity
			Gini Coefficient
			Poverty
			Voter Participation
			Childcare Availability
		Safety	Natural Disaster Related Deaths
			Disaster Related Economic Losses
			Resilience Plans

		Population Living in Disaster Prone Areas
		Emergency Service Response Time
		Police Service
		Fire Service
		Violent Crime Rate
		Traffic Fatalities
	Food Security	Local Food Production

Table 12- List of KPIs for Smart Sustainable Cities. Adapted from (U4SSC, 2017)

Appendix IV – Interview Summaries

"Interviews were held through Microsoft Teams, some were held in Dutch and some in English. Microsoft Teams was used to record and transcribe the interviews. To translate and summarize the interviews for the appendix, generative AI tools were utilized. To request the original interview recordings, contact the author of this paper. For the paper itself, only the original recordings and transcripts were consulted. "

Expert 1

The Program Manager from Digital City Rotterdam discussed their holistic approach to viewing the city as a digital ecosystem. They emphasize that the city is no longer just a physical space but a combination of social, physical, and digital realities. The city is undergoing a shift from a social-physical entity to one in which digital elements are integral.

Some people still see digital technology merely as a tool within the physical world, while others view it as a reality parallel to our own, which continuously surprises and challenges our current understanding. The expert highlighted issues such as data privacy and governance, particularly in light of the significant dependence on digital infrastructure, which became apparent during pandemic events.

The concept of 'Digital Twins' is pivotal, referring to a detailed digital model that represents the physical city, which is continuously updated using actual data from various sources. This concept aims to create a shared and collaborative environment to manage the city more efficiently, transcending the constraints of traditional, compartmentalized approaches.

An 'Open Urban Platform' is being developed in Rotterdam, serving as a hub for data and digital communication within this ecosystem. This platform addresses not only data integration but also embraces social elements through co-creation tools, allowing citizens and the council to discuss and plan their city's spaces effectively. This could potentially include elements like park benches or trash cans.

Moreover, the expert envisions the future of urban living, where digital and physical realities converge to shape our daily lives, advocating for the integration of digital infrastructures into urban governance. They underscore the importance of community involvement and suggest a need to rethink how public spaces are used as the younger generation engages more in digital environments.

The discussion also extends to the role of the local government and other stakeholders in managing and regulating digital spaces to ensure they serve public interests, not just those of big tech companies. The aim is to create transparent, responsible, and inclusive digital environments, potentially by establishing a governing board to oversee operations in areas where regulations may not yet exist.

Finally, the expert mentions European initiatives and the OASC (Open & Agile Smart Cities), which is a network focused on establishing common frameworks for cities to develop and manage their digital infrastructure. They underline the need for shared standards (like universal connectors or stekkers in Dutch) to allow seamless data flow and integration between various systems and services within the city's ecosystem.

In summary, the interview arranges the future of city management as a squad that needs to integrate digital capabilities into everyday governance to improve urban living, emphasizing the importance of using technology to foster collaboration, sustainability, and citizen engagement.

Expert 2

The researcher speaks with the expert about the concept of an Urban Digital Twin within the context of the expert's work at OASC and the City of Ghent. They explore the use of digital twins in city planning, particularly for helping cities operate more autonomously and achieve sustainability goals established by the United Nations.

The conversation initially delves into explaining what a digital twin is and what it should be capable of, emphasizing ecosystem components and self-regulation within a city. The expert brings up the Minimum Interoperability Mechanisms (MIMs) developed by OASC as essential for facilitating faster, more accessible, and cheaper data exchange between governments, ideally without being restricted to specific vendors.

The researcher notes that a significant challenge in smart city development is interoperability. The expert outlines OASC's work on different types of open standards related to contextual information and initiating real-time dynamic systems.

As the interview progresses, the expert articulates his interest in "self-regulation and ecosystem," remarking on the importance of creating an inclusive digital city model that involves stakeholders beyond the government, including citizens, businesses, and organizations. He introduces the concept of "passive participation," where the city collects data on citizens' sentiments about urban interventions without requiring their active participation.

The expert speaks about the use of digital twins for more transparent urban planning. For example, project developers could instantly see why a design does not comply with regulations, leading to quicker adaptations. This transparency in decision-making is discussed as a potential remedy for issues like bureaucratic delays and fostering trust among citizens and stakeholders.

The expert expresses enthusiasm for the researcher's approach and offers to provide further case studies and examples of digital twins in action across Europe to enhance the research. He also mentions an interesting case from Sofia, Bulgaria, which could contribute valuable insights into the ecosystem-based approach and open-source philosophy in digital urbanism.

The dialogue was constructive, offering insights into how smart cities might evolve through collaborative efforts and innovative technologies like digital twins.

Expert 3

In this extensive and enlightening interview, the researcher engages with the program manager for digital twin Utrecht (the expert) for a discussion on the concept of a holistic urban digital twin. They explore the transition from traditional 2D city mapping to more dynamic and integrated 3D digital twins. The expert emphasizes the importance of such digital twins in urban planning, highlighting how they are crucial for visualizing and managing the multiple challenges cities face today.

The discussion delves into how digital twins are currently used more as visualization tools than decision-making ones. However, the expert envisions a future where digital twins are integrated with real-time data and AI to significantly enhance urban management. They talk about how cities like Munich are already using AI to query digital twins for various data, such as finding the highest buildings, which highlights the potential for AI integration.

Ethical considerations play a crucial role in the conversation. The expert points out that while a plethora of data can be integrated into these digital twins, care must be taken to ensure privacy is protected and not overwhelm the public with too much information or misrepresent the data.

They also discuss the concept of participatory city planning, where digital twins can empower citizens to get directly involved in city developments. The expert shares insights into how digital twins can be openly available for individuals to add data and use it for personal projects, supporting democratic participation in urban development.

The interview touches on the integration of sensor data into digital twins, like heat maps updated four times a year, and the potential to move towards constant updates as sensor technology improves and becomes more widespread. This leads to thoughts on evolving the digital twin into a living model that reflects the rhythm of city life in real-time.

Finally, the expert assures the commitment to open standards and open-source models, providing the codebase on GitHub for public access. He underlines the need for collaboration within the ecosystem, consisting of public authorities, citizens, and private companies, to advance digital twin technology without falling into a vendor lock-in.

Overall, while acknowledging technological strides, the expert points towards the vast potential of urban digital twins yet to be harnessed, stressing the need for ethical, participatory, and inclusive approaches to their development and application.

Expert 4

In this interview, the researcher speaks with an expert on smart cities about developing sustainable urban environments and planning for future scenarios using real-time data. The conversation revolves around two main areas:

Implementation of Urban Digital Twins: The expert confirms that they are indeed working within several thematic areas of urban development, such as energy, mobility, water management, and interventions specific to certain developments, in order to leave urban educational areas in a better state than they were found. The researcher's research focuses on using real-time data to simulate interventions and test their impacts in various city environments, considering both the environmental and social aspects.

Current Decision-Making Process in Cities: The expert explains that many decisions are still made traditionally, through reports and assessments by external experts. They utilize digital tools like Tygron and NL Greenlabel for environmental intervention simulations. Moreover, the conversation touches on the importance of having a single source of truth when it comes to data. The expert mentions that while some data is readily available, the challenge lies in ensuring the quality of that data and protecting individual privacy.

The researcher asks how cities decide whether to implement solutions and interventions in urban areas. The expert emphasizes that much of the decision-making is still handled traditionally, with experts writing reports and conducting assessments. The challenge is that not all ambitions and repercussions can be fully accounted for within current methodologies, leading to potential oversights and additional iterations required during urban planning processes.

Regarding the future of city planning and digital integration, the expert sees it as a collaborative effort between tool developers, software companies, and municipalities. The most important aspect is the standardization of data and formats to ensure that all cities can use the same tools effectively. They also discuss the involvement of housing associations and the importance of sharing knowledge and resources for future development.

The expert also expresses caution about making data too openly available, highlighting the risks of data misuse and the importance of non-identifiable data in public use. They stress that cities have an abundance of data, but managing it responsibly is crucial.

The United Nations Sustainable Development Goals are brought up as a framework for city indicators that can guide better urban planning and decision-making. The expert acknowledges the practical use of these indicators, although he notes that there are political nuances and trade-offs in applying them across different city regions.

In conclusion, the interview sheds light on the complexities of urban development, the need for quality data, standardization, responsible data management, and the convergence of multiple sectors and stakeholders to create cohesive, sustainable, and smart cities that serve their inhabitants effectively.

Expert 5

In this detailed exchange, the researcher spoke with an expert about urban digital twins and their implications for city management. The expert, an academician with a geomatics background from the University of Liege, is focusing on overcoming data integration challenges within urban digital twins. The expert's approach seeks to provide conceptual guidelines for integrating diverse data types, ranging from spatial data to specific thematic data, into urban digital twins.

The discussion delves into the notion of digital twins as more than just technological constructs; they represent a shift toward integrated, data-driven city management. Both the researcher and the expert emphasized the importance of collaboration across various domains—government, industry, and academia—to ensure the digital twin accurately reflects the city's multifaceted nature.

The expert's work aims to benchmark current digital twin initiatives to identify and propose integration levels that could make urban digital twins more effective in real-world applications. This involves understanding not only the technical aspects but also the conceptual underpinnings that make urban digital twins valuable for city planning, environmental monitoring, and other applications relevant to urban development and sustainability.

Special attention is given to the concept of citizen participation within the digital twin framework. The expert suggests that involving citizens more at the project's end or during the prototype phase might be more effective, as it allows for direct interaction with a tangible digital twin model. This approach differs from earlier stages, where expert input predominates in developing the model's framework and data layers.

Key challenges highlighted include the variability of data standards, the quality and completeness of data, and issues surrounding data sharing and privacy. The expert underscores the need for clear definitions and standards to aid in the integration process, recommending a focus on generic frameworks that can adapt to various urban contexts and scale from city to regional levels.

As the conversation concludes, the expert encourages the researcher to pursue a holistic model that encompasses broad stakeholder involvement and to consider how such a model could be practically implemented in specific case studies or use cases. This emphasizes the potential of urban digital twins as collaborative platforms that utilize both expert insights and citizen feedback to enhance urban management and planning.

Expert 6

In an engaging interview, the researcher, converses with an expert from the municipality of Utrechtse Heuvelrug, discussing the nuances of implementing smart technology within city management. The researcher is curious about smart systems that manage traffic and improve air quality through simulations and data integration. He questions how municipalities manage and trust the data needed for such modeling, highlighting its importance for decision-making processes.

The expert addresses the complexity of the researcher's questions, starting with the municipality's stance on the development of 3D technology and its use in enhancing public services. Although the expert finds the concept promising, he notes the cost-prohibitive aspect for small municipalities and the current lack of practical implementation within Utrechtse Heuvelrug. He stresses that the quality of existing registrations, like the Basisregistraties Adressen en Gebouwen (BAG), is integral to future advancements in 3D technology, such as the Digital Twin initiatives, and believes that the groundwork in data quality needs to be solid before expanding into such terrains.

The expert discusses two types of municipal developments: those that require consent and are therefore meticulously recorded, versus independent actions by residents or businesses where monitoring is less stringent. The researcher asks about the transition from 2D to 3D modeling in granting building permits, and the expert informs him that although architectural assessments could benefit from 3D models, legal and practical frameworks have yet to catch up, often leaving the decision to use such models at the discretion of individual municipalities.

The conversation shifts to the operational aspects, with the researcher seeking insight into the practical implications of 3D mapping for utilities like pipelines. The expert details the municipality's efforts to model its networks but acknowledges that comprehensive 3D mapping is not standard practice across all utility management. He touches on the importance of having detailed models, particularly in busy urban areas, where the stakes are higher for maintenance and planning.

Data privacy and the risks of making detailed data publicly available have become a focal point. The expert contextualizes the dilemma, suggesting the need for a delicate balance between leveraging data for public benefit and avoiding privacy invasions or discriminatory practices. The researcher and the expert agree on the need for careful consideration of the level of detail shared, particularly when private entities or AI are involved in decision-making.

Toward the end, the expert and the researcher delve into the possible futures of municipal technology adoption. They discuss open-source software, comparing its collaborative nature to proprietary systems, which often lock municipalities into particular vendors. They reflect on the benefits of open standards, which enable different systems to 'speak the same language,' thus facilitating integration and interaction.

The expert from Utrechtse Heuvelrug underscores that while innovations like Android's open-source approach offer opportunities, there are also challenges in terms of standardizations and vendor influences. They conclude by discussing the global movement towards open standards and the significant effort required to ensure that these standards lead to meaningful and interoperable solutions in smart city contexts.

In summary, this enlightening conversation highlights the cautious optimism of Dutch municipalities as they navigate the opportunities and challenges presented by smart city technologies, ensuring that any advancement is purposeful, inclusive, and respectful of its citizens' privacy.

Expert 7

In this conversation, the researcher engages in a detailed discussion with a project manager at IT & Smart Cities (the expert) regarding the implementation and implications of smart city initiatives, particularly focusing on self-regulating digital twins for cities. The interview opens with introductory pleasantries before shifting to the core discussion about the expert's work with the West Flemish inter-municipal cooperative, which assists 54 West Flemish municipalities in transitioning to future-proof practices in several areas including mobility, sustainable living, entrepreneurship, climate, and smart cities.

The expert elaborates on the various aspects his department, Data, and Technology, deals with, emphasizing the interdisciplinary nature of smart city projects that blend technology with mobility, climate, and other areas. He mentions working with cities like Bruges, Roeselare, and Oostend on smart city projects and acknowledges the financial and resource disparities between large cities and smaller municipalities.

The conversation delves into the potential and challenges of urban digital twins. The expert outlines the approach to collecting existing data from larger organizations and collaborating with technology partners and academic institutions to develop innovative, often subsidized projects. He highlights the inefficiency and impracticality of isolated municipal digital twin projects due to resource constraints and underscores the collaborative efforts led by entities like Digital Flanders and the European Union to provide centralized building blocks for digital twins.

The expert discusses how to use open data platforms such as Urban Sense, which specializes in integrating volatile data for municipal use. Another point of discussion revolves around privacy concerns, the availability of open data, and the complexities of data management, including the varying standards and semantics used to describe similar entities across different datasets.

The conversation also touches upon artificial intelligence's increasing role in municipal projects, with the expert pointing out the widespread interest in AI and its integration into various projects, including traffic management, air quality monitoring, and even analyzing thermographic images of buildings to detect insulation deficiencies.

Towards the end of the discussion, the researcher shares his vision for his research project, aiming to design a system that fosters collaboration across various sectors within a city to achieve self-regulation based on real-time data and simulations. The expert responds positively to this idea, emphasizing the importance of centralization and cooperation in achieving efficient and cost-effective smart city solutions.

In summary, the interview explores the intricate landscape of smart cities, highlighting the importance of data integration, collaboration, and leveraging new technologies like AI to enhance urban management and planning. The expert's insights reveal the potential for advanced digital twins to support evidence-based policymaking, provided there are concerted efforts to standardize data and foster collaborative ecosystems that include governmental bodies, private entities, and citizens.

Expert 8

In this discussion between the researcher and an expert in the field of digital twins and smart cities, a wide range of topics related to the development, implementation, and research of digital twins in urban environments were covered.

The expert emphasized the importance of designing a digital twin that bridges the gap between technology and business operations, especially in an urban context. The focus was placed on the need to develop a platform that is not only focused on the technological aspect but also on the interaction with the ecosystem and how self-regulation can contribute to a digital twin evolving into an intelligent entity that effectively contributes to city management.

Various points were discussed, including the challenges of integrating different data platforms and the importance of open standards for data exchange. The use of existing infrastructure and connections between previously separate data sets plays a crucial role in creating a robust digital twin.

Furthermore, the conversation addressed the need for good governance and a collaborative framework to ensure the successful implementation of digital twins in urban areas. There was also a call for research into the economic value and operational models of digital twins, with seamless data integration and policy simulations seen as essential for accelerating policy cycles and strengthening data-driven decision-making.

Finally, it emerged that, although technology is advancing rapidly, there is still a significant need for research and development work to fully integrate digital twins into the everyday management and policy practices of cities, particularly in the areas of model integrity, data standardization, and the full disclosure of non-hard city-data.

Expert 9

In this detailed conversation between the researcher and the expert, the discussion revolves around the development, implementation, and future prospects of Digital Twins in cities, with a specific focus on Rotterdam's 3D project led by the expert. The expert, who is contracted by the municipality of Rotterdam, shares insights on the creation of a digital 3D representation of the city, which is updated annually through aerial imaging and LiDAR scanning. This approach aims to achieve the current model of the city, which supports various applications, including analysis platforms in the cloud.

The expert emphasizes the importance of open standards for data, as well as the potential challenges and considerations of integrating open-source solutions. Highlighting the importance of avoiding vendor lock-in, the conversation explores the benefits of open standards for maintaining flexibility and control over data and software. The expert illustrates how Rotterdam's strategy involves decentralized cloud storage across different platforms, each optimized for specific tasks, to manage the vast volumes of data generated by the city's 3D project.

Furthermore, concerns about data privacy, the influence of data-driven insights on insurance and property values, and the legal nuances of using architectural designs within digital twins are discussed. The expert also reflects on the collaboration between cities, both nationally and internationally, to share best practices and standards, emphasizing how this collective approach can lead to more efficient and effective development of digital twins.

Throughout the conversation, it becomes clear that while the technological foundation for digital twins is increasingly robust, the broader implications for governance, privacy, legal rights, and data management present ongoing challenges that require careful consideration and collaboration across sectors.

Expert 10

In a comprehensive discussion on the development and implications of Urban Digital Twins (CityOS), the researcher and the expert delve into how these systems can be implemented to make cities self-regulating through the use of real-time data and simulations. Their conversation encompasses technical, ethical, and governance aspects of CityOS, providing a multifaceted view of the future of urban planning and management.

The researcher introduces the subject by outlining their research focus on creating an urban digital twin capable of making cities self-regulating. They explain that their interest lies in collecting city data, such as air quality and heat stress maps, to run simulations to test different interventions. The researcher points out that their approach is more about the overall design and governance of such systems than the technical intricacies.

The Expert: Acknowledges the complexities involved in managing and implementing AI and digital twins within urban settings. They share insights from their experiences, highlighting how similar technologies are already being used in healthcare for predictive maintenance of medical systems and patient care optimization.

The expert elaborates on two main areas within Philips where digital twins play a critical role – operational efficiency in hospitals and patient-specific research. They describe how real-time data from various sources is utilized to predict equipment failure, thereby planning maintenance activities without disrupting hospital operations. In terms of patient care, the expert discusses how real-time data monitoring helps to predict potential health setbacks post-surgery, enabling preemptive care actions.

The conversation shifts towards how urban digital twins can inform decision-making in cities, specifically around heat management and urban planning. The expert notes the importance of harnessing both AI-driven and knowledge-driven models to analyze and interpret city data effectively. They distinguish between these models, explaining that AI-based predictions are purely data-driven, while knowledge-driven models incorporate physical laws and empirical data.

Addressing ethical considerations and data privacy concerns, both the expert and the researcher emphasize the criticality of setting strict guidelines and guardrails to ensure the responsible use of urban digital twins. They touch upon the potential risks of incorporating sensitive data into these systems and underscore the need for robust security measures to prevent misuse or cyberattacks.

In closing, the expert remains optimistic about the future of digital twins, envisioning broader applications across city planning, healthcare, and beyond. They stress the importance of purposeful implementation and clear objectives in realizing the full potential of these technologies.

Their dialogue paints a picture of a future where cities can become more adaptive, sustainable, and efficient through the integration of urban digital twins. Yet, it also casts light on the significant challenges ahead, including ethical boundaries, data privacy, and security considerations

Appendix V – Use Cases CityOS

In this section use cases will be shown for how each stakeholder group could utilize CityOS.

Self-Regulation

Use Case: Autonomous heat regulation in the city

Scenario: A city struggles with the effects of urban heat island effects where the city experiences higher temperatures than outside of the city. Due to large buildings and roads, the sun's heat is trapped in the city during the summer months. The city also relies on its green spaces as a natural cooling agent.

Objective: CityOS aims to autonomously manage and mitigate the heat of the city, ensuring the well-being of the population and the health of green spaces in the city.

System Process (Fig. 14):

1. Data Collection: Multiple IoT sensors deployed throughout the city monitor the temperature, air quality, and traffic flow. Local social media sentiment analysis tracks whether the population is experiencing excessive heat.
2. Real-Time Analysis: A "Heat Management Digital Twin" simulates this data in a real-time model, using AI to forecast temperature spikes and identify heat hotspots in the city.
3. Autonomous Decision Making: When heat hotspots are detected, the system autonomously triggers different pre-determined interventions such as:
   - Activating water sprinklers in green spaces to avoid greenery drying out.
   - Adjusting traffic signals to reduce congestion and reducing car-induced heat and pollution.
   - Sending public alerts to the population about the heat.
4. Predictive maintenance and feedback loop: The system forecasts when green spaces will require more maintenance (like watering) to maintain their cooling effects. The system also keeps track of the success of the interventions by analyzing data creating a feedback loop for continuous improvement.
5. Citizen Participation: The system can also be linked to an interface where citizens can actively contribute data and help with refining data sets.
6. Long-Term Adaptation: The system can give the city the information it needs to determine the locations of new cooling interventions, such as the

placement of green roofs, the expansion of parks, or the improvement of buildings to reduce heat absorption.

7. Regulatory: Update the system to reflect local and global environmental regulations, ensuring that its decisions are in line with current policies and goals.

Outcome: By managing heat regulation based on real-time data and simulations the system helps the city mitigate the effects of heat islands in the city and maintain the well-being of its citizens.

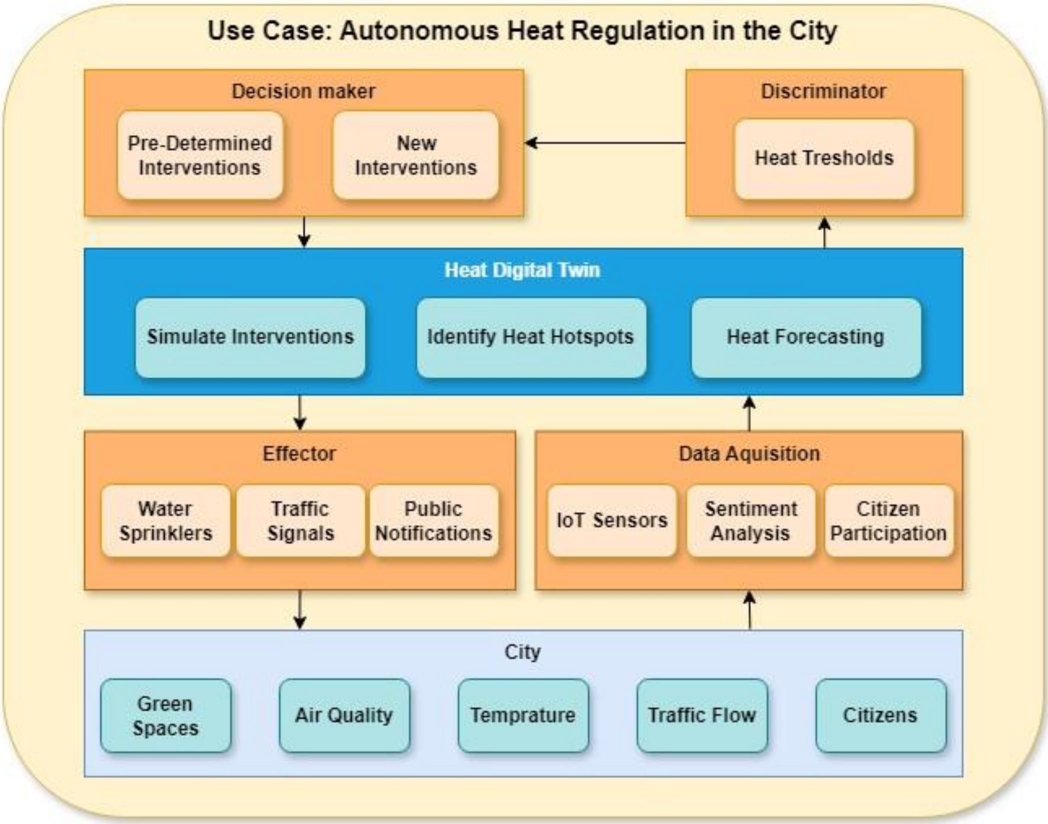

Figure 14 - Use Case: Autonomous Heat Regulation in the City

Public Organisations

Use Case: Efficient Waste Management

Scenario: A city is struggling with the efficient management of its waste disposal and recycling systems. The current operations are inefficient and the overflowing trash from containers pollutes the environment and impacts the well-being of citizens.

Objective: CityOS aims to optimize waste collection routes and schedules, minimize operational costs, and reduce environmental impact while providing a better service for the population.

System Process (Fig. 15):

1. Data Integration: CityOS integrates data from garbage trucks, sensor-equipped waste containers, citizen reports via smart apps, and waste processing facilities.
2. Intelligent Route Optimization: Using the data collected, a model is created where waste generation patterns are analyzed. Using these models optimal routes for waste collection can be simulated for efficiency.
3. Dynamic Scheduling: Based on the simulations, CityOS can be used to dynamically schedule waste collection, targeting areas with full waste containers first.
4. Citizen Participation: Citizens can report issues or schedule bulky waste pickups using an application that feeds into the model, allowing the routes to be dynamically adjusted.
5. Resource Allocation: Predictive analytics can be used to identify certain trends in waste production, allowing the municipality to allocate resources proactively.
6. Environmental Impact Monitoring: The system could track the environmental impact of waste management operations, like fuel consumption and emissions. This data can be used to minimize carbon footprints or be used in other models in the system.
7. Feedback Loop for Continuous Improvement: The system can constantly learn and make changes based on the data, which can improve the predictive models and efficiency of the operations.

Outcome: By managing waste management based on real-time data and simulations the system helps the city reduce costs, reduce litter, and improve efficiency.

Figure 15 - Use Case: Efficient Waste Management

Private Organization

Use Case: Sustainable Building Development

Scenario: A project development company aims to construct a new residential complex in the city. The company wants to ensure that the development not only complies with city regulations and environmental standards but also contributes to the local community and urban landscape.

Objective: Using CityOS, the company can design its residential complex so it aligns with the city's ambitions for sustainability, infrastructure, and community needs.

System Operation (Fig. 16):

1. Integration with CityOS: The development company gains access to the base models of CityOS system. These include a comprehensive model of urban geography, current infrastructure, zoning regulations, demographic dynamics, and environmental data.
2. Design Simulation and Analysis: The company uses the model to run simulations on their proposed building projects within the Digital Twin of the city. By doing this they can assess the impact of the building on the local environment and existing urban aesthetics.

3. Feedback System for Sustainable Features: The company could simulate different design alterations, like green rooftops, rainwater collection, or solar panels. By doing this they can visualize the environmental impact and validate it against the city's ambitions and goals.
4. Community Impact Assessment: The system can also allow citizens to participate in the design process by gathering feedback from potential residents and local businesses, ensuring that the new development serves the community's needs.
5. Visualization for Stakeholders: By deploying a simulation of the proposed development in the system it can be used to aid communication and negotiations with both stakeholders and regulatory bodies.
6. Compliance with Regulations: CityOS can keep the company up-to-date on all environmental and building regulations.

Outcome: By making use of CityOS, the development company can reduce project risk and ensure that the final development complies with building & environmental regulations, and is welcomed by the community. By using the system, the company can gain a competitive edge in the market.

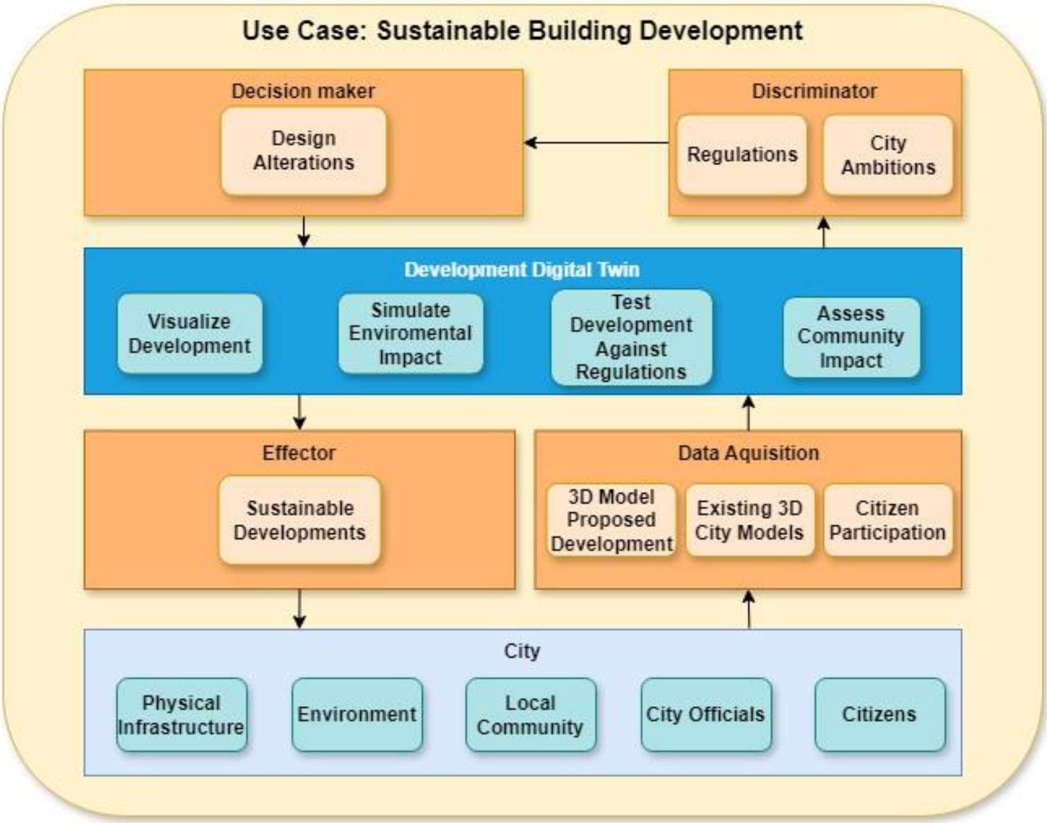

Figure 16 - Use Case: Sustainable Building Development

Academia

Use Case: Urban Resilience and Climate Change Adaptation Research

Scenario: A local university is researching climate change's impact on urban areas. Researchers at the university want to test different outcomes of interventions in the city.

Objective: The university's goal would be to utilize CityOS to model climate-related challenges within the city and explore the effectiveness of proposed solutions.

System Operation (Fig. 17):

1. Access to Comprehensive Data: Researchers can access climate patterns, infrastructure data, demographic statistics, and environmental conditions from CityOS by integrating them into a model.
2. Collaborative Research Platform: The department could collaborate with other universities and research institutions through CityOS, where they could co-develop new simulation models.
3. Simulation of Climate Scenarios: The academics can use CityOS to simulate extreme weather conditions like floods, extreme rainfall, or heat waves. The model can assess how such events affect the city.
4. Simulation of Interventions: The academics could also simulate the effectiveness of interventions like green roofs, flood barriers, or different sewage systems.
5. Policy Impact Analysis: Researchers can analyze the effects of proposed policy changes in the city like urban greening initiatives or revised zoning laws.
6. Public Education: Findings of the research can be shared with the public through visualizations and interactive models to engage citizens and gather feedback.

Outcome: The university can use CityOS to perform urban research projects and help improve the city’s urban and climate change resilience.

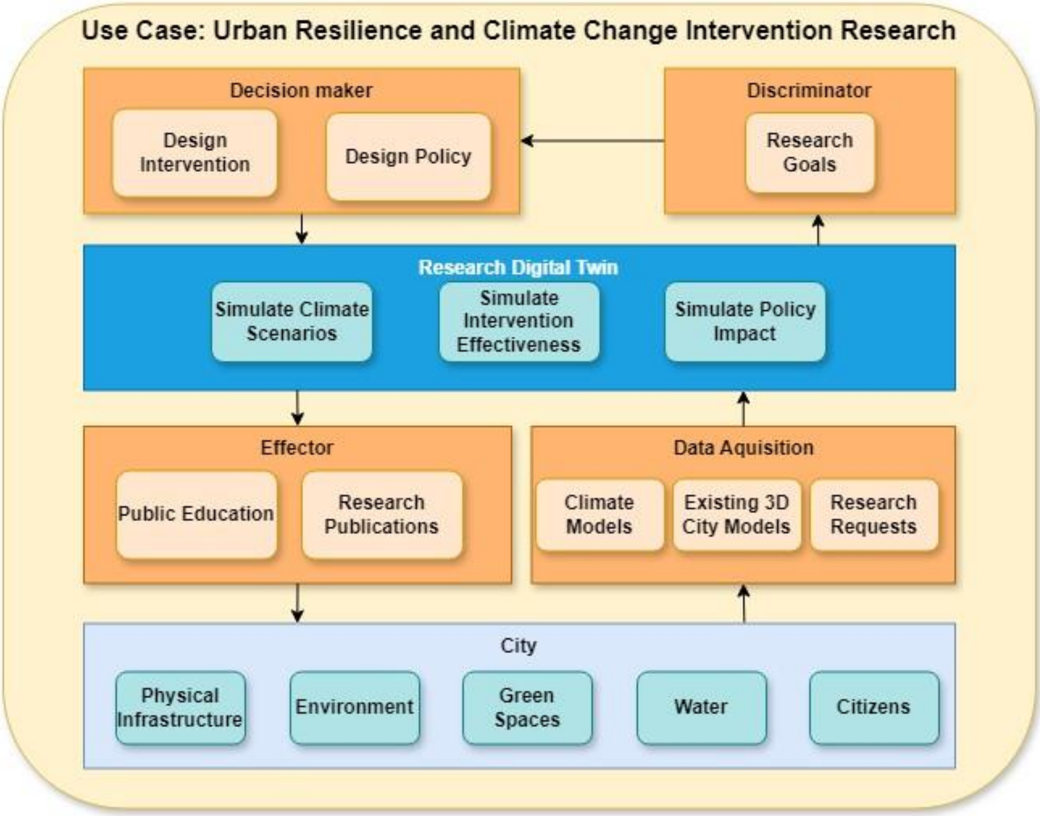

Figure 17 - Use Case Urban Resilience and Climate Change Intervention Research

Citizens & Communities

Use Case: Community-led Urban development

Scenario: A city wants to engage its citizens more and encourage participation in the development of the city.

Objective: Create a space where residents can come together to become active participants in the planning process of their neighborhood.

System Operation (Fig. 18):

1. Community Access to CityOS: the municipality provides access to CityOS for residents. People can log in through a community portal to view data, plan proposals, and participate in simulations affecting their neighborhood.
2. Interactive workshops: CityOS can provide a virtual place for workshops where residents can view and interact with realistic 3D models of proposed developments.
3. Citizen Feedback Collection: Residents can use CityOS to provide instant feedback on proposals, contribute their ideas, and express concerns or support for various initiatives.

4. **Data-Driven Community Proposal**: Using CityOS communities can propose locations for public amenities like parks, and community centers based on the data the system provides.
5. **Crowdsourced Urban Monitoring**: Citizens can use CityOS to report issues such as trash, damages to public property, or streetlight outages.

Outcome: By enabling citizens & communities to participate in the development of their neighborhoods, they gain a sense of ownership and pride in the transformation as their shared vision shapes the future of their community.

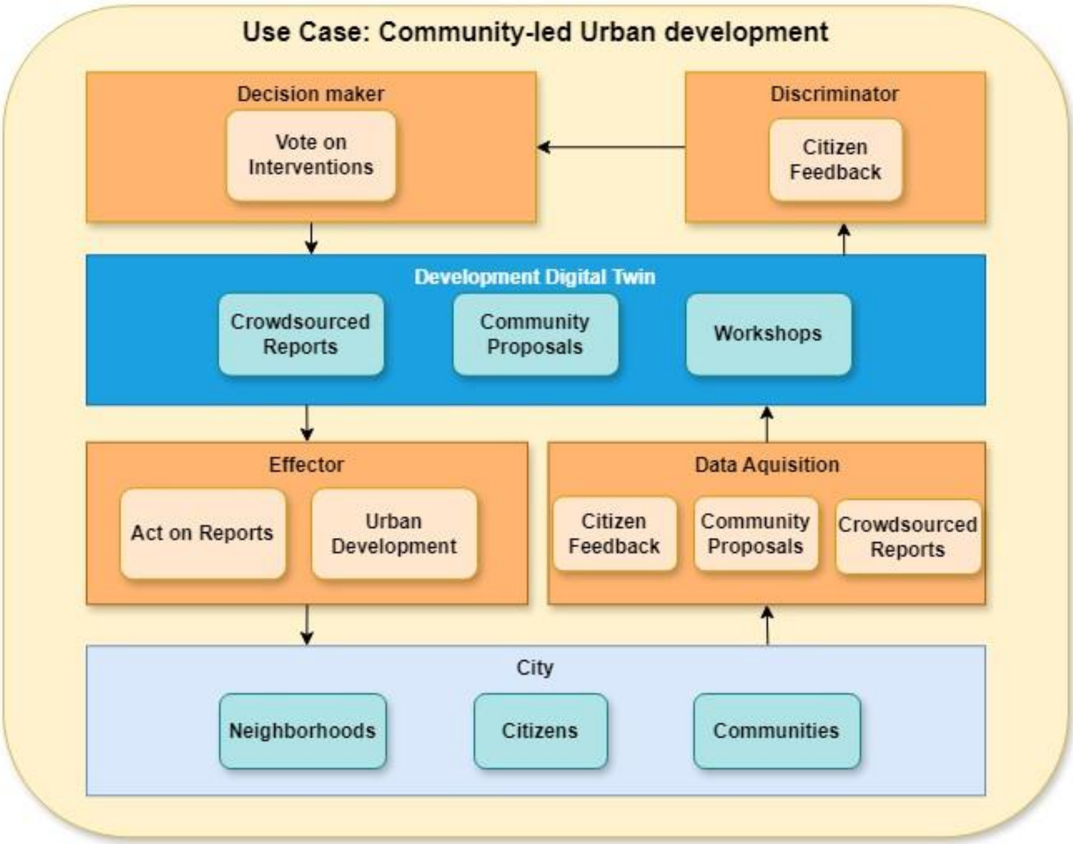

Figure 18 - Use Case: Community-led Urban Development

Appendix VI – CITYSTEPS maturity model

Stage:	Description:
1: Preparation and Planning Stage.	The initial stage is where the UDT is being planned and prepared.
2: 2D Stage	The second stage is when data is incorporated into a 2D model.
3: 3D Static Stage	The third stage is when static data is used to build a digital 3D city model.
4: 3D Dynamic Stage	The fourth stage is when the digital 3D model includes dynamic data from the city which can be used to simulate basic scenarios.
5: Dynamically integrated 3D stage	The fifth stage the UDT incorporates 3D dynamic and IoT data. From this stage onwards the model can include imaginary structures that don't yet exist.
6: Real-Time Decision Making Stage	In the sixth stage, the UDT gains capabilities to analyze dynamic and integrated 3D data, offering accurate insights and real-time data alternative options for decision-making. And can simulate impacts across different domains.
7: Autonomous Decision-Making Stage	In the seventh stage, the UDT uses autonomous reasoning and AI to make decisions independently and execute actions based on predictions and simulations.
8: Real-time Synchronisation and Autonomous Implementation Stage	In the eighth stage, the UDT achieves full, bidirectional, continuous, real-time synchronization between the physical reality and the digital counterpart. The UDT autonomously implements decisions, guided by insights from simulations.

Table 13 - CITYSTEPS Maturity Model. Adopted from (Haraguchi et al., 2024)