FINLAND FUTURES RESEARCH CENTRE • UNIVERSITY OF TURKU

EXPLORING SMART CITY DIGITAL TWINS

From Distinct Concepts Towards Integrated Socio-Technical Applications

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SUMMARY

In the research-based e-book report of the Smart City Digital Twins (SCDTs) project, we have provided different conceptualization approaches on Smart City and Digital Twins, then attempt to merge those varying concept-lines with general guidelines for data management and knowledge management. It was a difficult task to bring together the smart city and the digital twin concepts into one common denominator. Smart cities can be defined as socio-technical urban systems. Cities are a social system with dynamics of people, goods, culture, bio-diversity, sustainability, and creativity. Technical systems of these complex social system require intense technological infrastructures. Thus, the collection, extraction, consistency of the data in smart cities as socio-technical systems should ensure city planners, businesses, people to make current and future-oriented informed-decisions by considering all the urban data within cities. Further, this requires more data management and the integration of data sets into real urban planning processes. The essential challenge is the integration of data/information systems concerning each other and the development of systemic entities in cooperation with expert groups and experts from different professional areas of urban planning.

The concept of digital twins can be considered only if smart city reaches essential maturity, because digital twins, with their basic definition, are the real-time replication of a process, product and systems in digital environments. In this regard, various feasible frameworks and methods have been presented whether a city's smart city initiatives have sufficient maturity e.g., for digital twin integration. Maturity of smart city and its systemic urban planning entities can be examined from the Smart City Wheel framework, as shown in the research report.

Also, in this final report, we identified ten key challenges of the co-creation of smart cities and digital twins and presented them in the following Policy Brief section. Often these dossiers have been developed in isolation, which is a problematic approach in many ways. This was also an important strategic issue and a key challenge for the Smart City Digital Twins project.

This publication is the final report of the Smart City Digital Twins project, which includes the following topics. In **Chapter 1**, we motivate the readers of our report on the different themes of Smart City Digital Twins development activities. The Smart City Digital Twins challenge affects all public sector and urban developers, as well as businesses and industry, the academic research community, and civil society actors (i.e. the so-called "Digital Twins"). Quadruple Helix stakeholders). In **Chapter 2**, we introduce readers to the content discussion of both Smart City and Digital Twin concepts and recent scientific developments in the field. In this context, we see that scientific research today provides a strong case for the development of smart cities and digital twins. In **Chapter 3**, we provide a methodological overview of the foresight and urban planning methods used during the project, which were also piloted in the project. In Chapter 3 Boyd Cohen's Smart City Wheel approach is introduced and data collection/management framework of urban city studies is explained. In Chapter 3, we also explain Benchmarking, Bench-learning, and Bench-action Process approach, participatory hybrid foresight framework, and applied case study framework of cities. In **Chapter 4**, we report insights into smart city digital twins' development from urban case studies (Turku, Gdańsk, Wrocław, and Vilnius). Insights are based on qualitative and quantitative analyses. In **Chapter 5**, conclusive remarks and reflections are presented.

TIIVISTELMÄ

Smart City Digital Twins (SCDTs) -hankkeen aikana tehdyssä tutkimukseen perustuvassa e-kirjaraportissa tarjoamme erilaisia käsitteellisiä lähestymistapoja älykkään kaupungin käsitteeseen (Smart City) ja digitaalisiin kaksosiin (Digital Twins). Olemme pyrkineet yhdistämään nämä kaksi käsitettä loogiseksi kehittämiskokonaisuudeksi, joka sopii myös yleisiin tiedonhallinnan periaatteisiin ja tiedonhallinnan ohjeisiin. Älykaupungin ja digitaalisen kaksosen konseptien yhdistäminen yhdeksi yhtenäiseksi käsitteelliseksi kokonaisuudeksi oli vaikea ja haastava tehtävä. Älykäs kaupunki voidaan määritellä sosio-teknisiksi kaupunkijärjestelmiksi. Kaupunki kokonaisuutena on sosiaalinen kokonaisjärjestelmä, jossa on sisäänrakennettu ihmisten, tavaravirtojen, kulttuurin, biologisen monimuotoisuuden, kestävyyden ja luovuuden systeeminen dynamiikka. Monimutkaisiin sosiaalisiin järjestelmiin kytkeytyvät erilaiset tekniset järjestelmät edellyttävät toimiakseen mittavia teknologisia infrastruktuureja. Näin ollen älykkäiden kaupunkien toiminnassa tarvittavien tietojen keräämisen, datan valikointi ja sosio-teknisen järjestelmän toimivuus olisi varmistettava kaupunkisuunnittelijoiden, yrityksien ja ihmisten yhteistyönä. Näin toimien voidaan varmistaa älykkäiden kaupunkien dataan, informaatioon ja tietoon perustuva päätöksenteko nykytilanteessa ja tulevaisuuden haasteiden osalta. Tämä toiminta edellyttää yhä enemmän tiedonhallintaa ja laajojen data- ja tietoaineistojen integrointia todellisiin reaaliaikaisiin kaupunkisuunnitteluprosesseihin. Iso ja keskeinen haaste on toisiaan koskevien tietojärjestelmien keskinäinen integrointi ja älykkäiden kaupunkien systeemisten kokonaisuuksien kehittäminen yhteistyössä kaupunkisuunnittelun ammattialojen asiantuntijaryhmien ja yksittäisten asiantuntijoiden kanssa.

Digitaalisen kaksosen konseptin käyttöä ja hyödyntämistä voidaan harkita vain, jos älykaupunki saavuttaa olennaisen datan ja tiedonhallinnan kypsyyden, sillä digitaaliset kaksoset ovat perusmääritelmineen prosessin, tuotteen ja järjestelmien reaaliaikaista replikointia digitaalisissa ympäristöissä. Tähän haasteeseen liittyen on esitetty erilaisia toteuttamiskelpoisia viitekehyksiä ja menetelmiä. Voimme kysyä¨, ovatko älykaupunkialoitteet ja kaupunkien datan ja tiedon hallintaprosessit riittävän kypsiä digitaalisen kaksosen keskinäiseen toiminnalliseen integraatioon? Älykkään kaupungin ja sen systeemisen kaupunkisuunnittelun kokonaisuuksien kypsyyttä voidaan tarkastella Älykkään Kaupungin Pyörän (Smart City Wheel) pohjalta. Älykkään kaupungin ja sen systeemisen kaupunkisuunnittelun kokonaisuuksien kypsyyttä voidaan tarkastella Smart City Wheel -viitekehyksestä, kuten tästä tutkimusraportista käy ilmi.

Tässä hankkeen loppuraportissa tunnistimme kymmenen eri älykkäiden kaupunkien ja digitaalisten kaksosten yhteiskehittämiseen liittyvää keskeistä haastetta. Esittelimme ne politiikkasuositusten yhteenveto-osiossa. Usein näitä eri asiakokonaisuuksia on kehitetty toisistaan erillään, mikä on monella tapaa ongelmallinen lähestymistapa. Tämä toisistaan erillään kehittämisen ongelma oli ärkeä strateginen kysymys ja keskeinen haaste Smart City Digital Twins -hankkeelle. Tämä julkaisu on Smart City Digital Twins -hankkeen loppuraportti, joka sisältää seuraavat luvut sisältöineen. **Luvussa 1** motivoimme raporttimme lukijoita Smart City Digital Twins -kehittämistoiminnan eri teemoista. Smart City Digital Twins -haaste koskettaa kaikkia julkisen sektorin kaupunkikehittäjiä, yrityksiä, teollisuutta. akateemista tutkimusyhteisöä ja kansalaisyhteiskunnan eri toimijoita. Digitaalisia kaksosia kehitetään viime kädessä näiden eri toimijaryhmien tarpeisiin (ts.

neljää Quadruple Helix sidosryhmää varten). **Luvussa 2** tutustutamme lukijat sekä älykkään kaupungin (Smart City) että digitaalisen kaksosen (Digital Twin) käsitteelliseen sisältökeskusteluun ja tämän alan tieteellisen tutkimuksen viime aikaiseen kehitykseen. **Luvussa 3** tarjoamme metodologisen katsauksen hankkeen aikana käytettyihin ennakointi- ja kaupunkisuunnittelumenetelmiin, joita myös pilotoitiin hankkeessa neljässä kaupungissa. **Luvussa 3** esitellään Boyd Cohenin kehittämä Smart City Wheel -lähestymistapa ja selitetään lukijoille kaupunkitutkimusten tiedonkeruu-/hallintakehys. **Luvussa 3** selitämme myös vertailuanalyysin, vertailuoppimisen ja vertailuoppimiseen ohjautuvan vertailutoiminnan kokonaislähestymistavan, osallistavan hybridiennakointikehyksen lähestymistavan ja kaupunkien soveltavan tapaustutkimusviitekehyksen. **Luvussa 4** raportoimme näkemyksiä älykkäiden kaupunkien digitaalisten kaksosten kehityksestä eri kaupunkien tapaustutkimuksista (Turku, Gdańsk, Wrocław ja Vilna). Näkemykset ja tulokset perustuvat kvalitatiivisiin ja kvantitatiivisiin analyyseihin ja ne ovat luonteeltaan pilottitutkimukseen perustuvia ja myös tulokset ovat pilottimaisia. Jatkossa analyyseissä voidaan käyttää samoja menetelmiä, mutta analyysien olisi hyvä pohjautua laajempiin data-aineistoihin ja informaatiolähteisiin. **Luvussa 5** esitetään pilottitutkimuksen johtopäätöksiä ja lisäpohdintoja.

POLICY BRIEF

This section is including short policy brief for national and local decision-makers and Quadruple Helix actors. In this report, we have provided general guidelines for data management of smart city digital developments. Data management requires more data management activities, and data management integration in the processes of city planning. The challenge is to integrate data systems and to see the systemic entities being developed in cooperation with different expert groups and experts from different fields of city planning. Systemic city planning entities can be seen from the Smart City Wheel framework, as shown in this report. We recommend using this SCDT framework.

Particularly, the first challenge is the protection of citizens' data and the organisation of proper data processing without major cyber security risks. For Smart City Digital Twins systems to be developed on a long-term and cost-effective basis, the internal information systems of these city data infrastructures must also be developed on a long-term basis.

Aligning with the first challenge, the second challenge stems from the European Digital Compass strategy and its national targets requires this kind of security-oriented long-run approach for data economy and management. If digital twins can be developed on a long-term basis, the basic functions of the data economy must be in order, because artificial intelligence and digital twins need data to function. For this reason, we strongly recommend that in the future, national Digital Compass strategies be drawn up in direct management relation to urban development in Finland and the European Union.

The third challenge shortly will undoubtedly be national and international cooperation in various international smart city networks (e.g. Smart City Networks). Smart City Network, Nordic Smart City Network, Smart City Institute Japan, Smart City Expo World Congress, Innocities, etc.). The systematic use of international experiences should somehow be organised effectively in Finland. We, therefore, recommend that this national strategy be implemented purposefully with concrete development measures for the data economy in cities. Data economy solutions should be logically and functionally linked to the development of digital twins in smart cities.

The fourth major strategic challenge is to take account of the different and specific needs of cities. In this context, it is good to bear in mind (1) comparative advantages, (2) resilience challenges related to urban resilience, and (3) territorial strategic development and innovation priorities, which should be linked to smart city development actions, in particular the region's Smart Specialisation Strategy (S3). This S3 strategy is the official strategy of the European Union, based on a strategy based on the Smart Specialisation Strategy (S3).

The fifth strategic challenge is to involve citizens in the development of a smart city. Citizens' participation should take place as widely as possible and per the low-threshold principle so that the services developed correspond as closely as possible to the wishes and needs expressed by citizens, now and in the future. This participatory grass-root SCDT approach would strengthen urban democracy in the future.

The sixth broader challenge is comparing smart city operating models, learning from comparisons, and concrete actions based on learning from comparisons. This so-called Benchmarking, Bench-learning, and Bench-action Smart City (B3SC) operating model is a recommended approach for smart cities that want to utilise digital twins as systematically as possible in their development work.

The seventh strategic challenge is the coordination of smart city development at the national level. It would be good to ensure national coordination of smart urban development professionally and nationally.

The eighth strategic challenge is to ensure that economies of scale are put into practice. This means a strategic shift from city-specific solutions to large-scale platform cooperation between cities, which can save public money significantly instead of developing different systems in isolation and without actively realising economies of scale. Compliance with this proposal would bring savings for both cities and the state.

The ninth strategic challenge is the Entrepreneurial Discovery Process (EDP) in the context of implementing an intelligent specialisation strategy. The regional S3 strategies developed should also be linked to the development of smart cities, in particular strategic cross-sectoral cooperation in the development and implementation of S3 strategies. The extensive EDIH cooperation network established by the European Union is also an important practical tool for strengthening regional growth business activities. This development area has recently been seen as a challenge in Finland, where a clear shortage of fast-growing growth companies has been identified. Today, the European Union emphasises cross-border innovation and its development (Cross-border Innovation Networks). The workshop process of four Baltic Seas cities carried out in the project followed this strategic orientation recommended by the European Union.

The tenth strategic lesson of the SCDT development project is linking the SDGs to the technical and social goals of smart urban development. Synergies between the digital and green transitions can be deliberately created, but this requires a close strategic eye and vigilance on the part of urban planners and decision-makers. Linking the Sustainable Development Goals to smart city development activities is, of course, a big question and challenge. Finding synergies in the context of digitalisation and the implementation of the green transition is very important for purely economic reasons.

The City of Turku has been a key player in the SCDT project. We propose the application of the above ten strategic doctrines in the city of Turku. In addition, we see a need for closer task force teamwork to achieve the benefits of smart city digital twins already shortly. Without city-level coordination, the SDGs can certainly be achieved, but certainly slower if coordination is not organised in the internal field of urban development. We recommend the strong task force approach in city planning processes in Turku.

10 KEY RECOMMENDATIONS FOR DATA MANAGEMENT IN SUCCESSFUL CITY PLANNING

1. Integration of Data Systems	6. Economies of Scale Implementation
Ensure seamless integration of data systems in city planning processes, leveraging expertise from diverse fields. Utilize frameworks like the Smart City Wheel to develop systemic entities.	Shift towards broad platform cooperation between cities to leverage economies of scale, saving public money and avoiding the development of isolated, city-specific solutions.
2. Addressing Differentiated City Needs	**7. Linking SDGs with Smart Urban Development Goals**
Tailor smart city development activities to meet the specific needs of cities, considering comparative advantages, resilience challenges, and regional strategic innovation priorities, aligned with the smart specialization strategy.	Align technical and social goals of smart urban development with the Sustainable Development Goals (SDGs), creating synergies between digital and green transitions through strategic planning and decision-making.
3. National Coordination of Smart City Development	**8. National and International Cooperation**
Establish professional and national coordination of smart city development at the national level to streamline efforts and maximize impact.	Foster strong collaboration in international smart city networks, such as the Nordic Smart City Network and Smart City Expo World Congress, to exchange knowledge and best practices.
4. Long-Term Development of Data Infrastructures	**9. Benchmarking for Learning and Action**
Establish long-term strategies aligned with European Digital Compass goals for developing Smart City Digital Twins systems, emphasizing data protection and proper processing to mitigate security risks.	Implement a Benchmarking, Bench-learning, and Bench-action Smart City operating model to compare and learn from smart city operating models, facilitating informed decision-making and continuous improvement.
5. Citizen Engagement	**10. Entrepreneurial Exploration and Cross-Sectoral Cooperation**
Prioritize citizen involvement in smart city development, employing low-threshold principles to ensure services meet citizens' expressed wishes and needs, thereby enhancing city democracy.	Link regional S3 strategies with diverse Entrepreneurial Discovery Process (EDP) activities and encourage strategic cross-sectoral cooperation to stimulate growth and innovation, leveraging tools like the European Digital Innovation Hubs (EDIH).

1. MOTIVATION FOR SMART CITY DIGITAL TWINS

The Smart City Digital Twins project has a project facing two challenging issues, smart city development and digital twin development. It can be said that both challenges are already very big in themselves, but responding to them at the same time is an even bigger challenge. This publication addresses this *dual challenge of smart city development and digital twin development.*

Today we can see a smart city to be a technologically modern urban metropolitan area that uses different types of electronic methods and sensors to collect specific data. Data can be collected from various data channels. Data can be small data sets, panel data set, or big data sets. *Data economy* is a crucial issue for smart city development.

All data can be analysed with algorithms and statistical tools. An algorithm is a set of well-defined instructions or rules designed to solve a specific problem (for example, city planning problem) or perform a particular task. In computer science, algorithms are essential for performing computations, data processing, and automated reasoning based on data. They form the foundation of computer programs and are used in various fields such as artificial intelligence, cryptography, and data analysis. Algorithms can range from simple procedures to very complex calculations, and multi-step processes, and they are fundamental to the functioning of modern technology. Information and knowledge gained from that data analysis is used to manage assets, resources, and services efficiently; in return, that data is used to improve future operations across the city.

Nowadays the notion of smart cities relies on a range of technologies – including the Internet of Things (IoT), mobile solutions, big data, artificial intelligence (AI), and blockchain. Because of this connection with technology, some interpretations and definitions of smart city are very technocentric. However, today also human concerns about city development are relevant issues. For example, questions about how smart cities will address issues such as data privacy and social exclusion are discussed more than before. Developing human-centric approaches to smart cities is essential for creating sustainable and inclusive urban environments that prioritize the well-being, happiness, and social and private needs of residents.

Human-centric smart cities prioritize citizen engagement and participation in decision-making processes. So called augmented digital democracy will be possible in smart cities. By involving residents in the planning and design of urban infrastructure and services, cities can better address the needs and preferences of the people who live and work there. Smart digital technologies should be leveraged to improve the quality of life for all residents, including access to healthcare, education, transportation, and public services. Human-centric approaches focus on creating inclusive solutions that enhance well-being and promote social equity. Human-centric approaches take human motivation, access, and skills seriously when planning interfaces of smart cities. Today sustainable development is a key aspect of human-centric smart cities. By integrating environmental considerations into urban planning and design, cities can reduce their ecological footprint, environmental pressures to biodiversity, mitigate climate change impacts, and create healthier living environments for residents. Smart cities should be accessible to all residents, also including those with disabilities or special needs. Human-centric approaches prioritize always universal design principles to ensure that urban infrastructure, transportation systems, and digital services are accessible to everyone. Human-centric smart cities also prioritize the protection of individual privacy and security. By implementing robust data governance frameworks and cybersecurity measures, cities can build stronger trust with residents and ensure that smart technologies are used responsibly and ethically. Overall, human-centric approaches are essential for creating smart cities that are inclusive, sustainable, and responsive to the needs of residents. By prioritizing people over technology and technological determinism, cities can harness the power of innovation to improve quality of life and foster vibrant, resilient communities.

The central challenging issue in this e-book is a concept of digital twin. A digital twin is a virtual representation of a physical object, system, or process. It's essentially a digital counterpart that mirrors the physical entity in real-time or near real-time. Digital twins are created using data collected from sensors, IoT (Internet of Things) devices, and other sources to replicate the behaviour, characteristics, and interactions of their physical counterparts. The use of digital twins has a huge potential via various technological apps. Digital twins offer numerous benefits, including predictive maintenance, optimization, product and service development, remote monitoring and control, and lifecycle management and products, service processes and brands. Digital twins can improve the smart management of tangible and intangible capital.

Predictive maintenance creates benefits because by monitoring the digital twin's data, organizations can predict when maintenance or repairs will be needed for the physical asset, reducing downtime, and preventing unexpected failures. This possibility can improve efficiency and productivity of companies and public sector agencies much. Digital twins enable organizations to simulate different scenarios and optimize processes to improve efficiency and performance. Organisations can development scenario libraries which help them in optimisation tasks. Digital twins are an integral part of product development and in manufacturing, digital twins can be used to simulate and test product designs before final physical prototypes are built, speeding up the development process and reducing R&D costs. It is possible for operators to remotely monitor and control physical assets with DT's, reducing the need for onsite presence and improving safety. Remote controlling has an important role for the global economy. Lifecycle management of products can be implemented with digital twins. Digital twins can provide valuable insights throughout the lifecycle of a product or service system, from design and manufacturing to operation and maintenance, and service delivery, helping organizations make informed decisions and optimize CLEMS resources (capital, labour, energy, materials, and services).

Overall, digital twins play a crucial role in enabling organizations to better understand, monitor, and optimize their physical assets and processes in today's increasingly digital world. Nowadays digital twins are commonly used in various industries such as manufacturing, healthcare, transportation, and urban planning.

2. TOWARDS SMART CITY DIGITAL TWINS

In this chapter 2, we discuss the key concepts and frameworks that underline the key concepts and development of Smart City Digital Twins. Firstly, we present the origins, concepts, dimensions, pillars, and standardization approaches related to smart cities. Secondly, we focus on what digital twins are and what capabilities they have. Thirdly, we integrate smart city and digital twin concepts and literature to discuss about smart city digital twins – definitions, examples, challenges, technological preconditions, and policy landscapes.

2.1. Smart City

Brief History

Within scholarly discourse, an abundance of literature attempts to interpret the exact meaning – or even an ideal definition – of the "smart city”. Retrospectively, it is argued that the origin of the concept is based on technological integrations into the service systems of mid-1800s cities (Peirce, Neal et al., 2013.; Yigitcanlar et al., 2018). The manual nature of registration and monitoring systems in the late nineteenth century in American West made it difficult for the federal government to manage demographic and economic developments. This challenge combined by the mismatch between the expanding complexities of economic dynamics and bureaucratic inefficiencies, provided chances for new innovations, integration of technology by Herman Hollerith. He created a mechanical tabulating machine to expedite data processing. After new mergers, his initial initiative formed Computing-Tabulating-Recording Company, which subsequently became International Business Machines, today known as IBM (Peirce, Neal et al., 2013, p. 67). In Finland smart city theme with digital city modelling approaches have been a long-run research interest (see e.g. Linturi & Simula, 2005; Van Den Besselaar & Koizumi, 2005).

Compared to that period, the current complex agenda – climate change, global pandemics, and sustainability – on urbanization which is expected to surge with approximately 70% of the world's population living in cities by 2050 (UN-Habitat, 2022), have put cities under the great weight of different external factors. Thus, starting from the late 1990s, while Information and Communication Technologies (ICTs) and digitalization trends have increasingly been integrated to the city services, subsequently, the definitional attempts, which continues in multi-disciplinary domains such as sociology, ecology, politics, and economics, has brought various approaches and conceptualization perspectives on smart city phenomena transitioning cities’ running operations more “smarter” (Finger & Razaghi, 2017).

Definition(s) and Conceptual Challenges

In recent years, academic and public discourse has continued to have an impact on urbanization's technological advancement. These powerful variables, which are driving systemic changes in urban services, have not only accelerated the integration of ICT innovations into city's mobility, resource governance, waste, and energy management systems, but have also affected the conceptualization and definitions of "smart cities". According to retrospective evaluations of Albino et al. (2015) and Coletta et al. (2019), external factors triggering cities' systemic responses to these shifts have caused researchers to propose concepts such as "wired cities", "cyber cities", "digital cities", and "intelligent cities". These efforts, however, have drawn criticism from scholars assessing them "self-congratulatory" (Hollands, 2008, p. 304) and “superficial” (Caragliu et al., 2011, p. 69). On the other hand, Lombardi et al. (2012) asserts that some contend that labels cities with “wired”, “cyber”, “digital”, and “intelligent”, which emphasize technology and infrastructure, ignore the human factor. Similarly, Hollands (2008) argues that retrospective labelling should be approached critically, emphasizing the value of beginning with people's current knowledge and skills rather of concentrating just on technology. In the same vein, Caragliu et al. (2011) found a favourable association between urban growth and human capital through quantitative research that took a critical stance on how technology dominates discourse about smart cities. In a thorough study of the literature, Albino et al. (2015) noted that the term "smart" in urban contexts frequently emphasizes “technology” when assessing a city's “smartness” which means cities are equipped with more advanced ICTs in their operations and services, they become “smarter”.

Komninos (2002) describes possible meanings intelligent (smart) city all of which are related to the concept of the smart city at that time;

- it entails the implementation of diverse ICTs and digital applications in urban areas, frequently combining concepts of the knowledge-based, cyber, digital, and wired city.
- it alludes to the application of ICTs to transform governance and living profoundly and fundamentally in a region.
- it might refer to geographical areas/districts that use ICTs to promote innovation, learning, knowledge sharing, and problem-solving incorporated of ICTs into urban environments and challenges.

Amidst such a broad initial definition attempt as Komninos did, since then, what constitutes a “smart city” appeared to be ambitious topic that spawned new agenda for actors such as IBM (Batty et al., 2012, p. 487), Nokia, CISCO, Microsoft, Intel and Siemens academia, research organizations, and local and national governmental bodies and recently European Union to bring novel high-level approaches to the concept of “smart cities” (Kitchin, 2014, p. 2).

Since Smart Cities market worldwide is projected to grow by 12.24% (2024-2028) resulting in a market volume of €152Bn in 2028 (Statista: Smart Cities – Worldwide Market Forecast), in particular, the increasing efforts of leading companies offering industrial business solutions to the smart city concept in the last 20 years are an expected initiative. Even so, in a way, the various definitional viewpoints to the smart city concept shown in Table 1 still valid and backings the essential argument that there is no clear globally accepted definition (Albino et al., 2015; Toli & Murtagh, 2020; Yigitcanlar et al., 2018).

Table 1. *Conceptualization approaches to the smart city.*

Smart City Concept	Reference
A smart city is defined as a high-tech intensive and complex city that uses new technologies to connect people, information, and city components, resulting in a more sustainable, greener city, competitive and innovative business, and improved living quality.	Bakıcı et al., 2013
Smart City – a digital landscape of connected sensors and devices creates millions of control endpoints generating real-time data during operations and facilitating automated actions.	Nokia
Smart city is a forward-thinking city with strong performance in the economy, people, governance, transportation, environment, and quality of life, founded on a wise mix of assets and activities. Smart city refers to the search for and discovery of intelligent solutions that enable modern cities to improve the level of services given to people.	Giffinger et al., 2007
Smart city is a concept of urban transformation that should aim to achieve a more environmentally sustainable city with a higher quality of life, that offers opportunities for economic growth for all its citizens, but with respect to the particularities of each locality and its existing inhabitants.	Toli & Murtagh, 2020, p. 8
Smart cities at which cities improve people's quality of life while minimizing environmental impact. The objective is to create a better society by constructing healthy, safe, and flexible cities that supply their citizens with services, energy, housing, and transportation options via a set of technology systems that assist cities in achieving their aims.	VTT Finland
Cities need to take advantage of their great ability of becoming smarter. They need to act quickly, transforming their basic systems with new technology to make the most use of limited resources. The city as a "system of systems" Smarter cities modify their systems as well as their "system of systems". A smarter city employs technology to change its essential operations and maximize the return on mostly finite resources.	IBM
Smart city is a city that increases the pace at which it provides social, economic and environmental sustainability outcomes and responds to challenges such as climate change, rapid population growth, and political and economic instability by fundamentally improving how it engages society, applies collaborative leadership methods, works across disciplines and city systems, and uses data information and modern technologies to deliver better services and quality of life to those in the city (residents, businesses, visitors), now and for the foreseeable future, without unfair disadvantage of others or degradation of the natural environment.	International Organization for Standardization (ISO)
Smart cities are boundless, regenerative, and vision-driven, resulting in a distinct - even radical - understanding of what it means to be "people-centric". The characteristics of cities are employed above to make technology advancements in cities as the servant rather than the master of people.	Demos Helsinki, 2020
A city where the potential of city can be harnessed through the power of digital technology to enable its residents to enjoy a high quality of life.	Tokyo Metropolitan Government 2023
A city is smart when it invests in people and social capital, as well as advanced ICT infrastructure, to drive long-term economic growth and a high standard of living, while also managing natural resources wisely via participatory government.	Caragliu et al., 2011

A smart city is also equivalent to a “smart sustainable city”, promoting economic and social development alongside environmental protection through effective mechanisms to meet the current and future challenges of its people, while leaving no one behind. As a city’s nature remains an important foundation of its economic development and competitive advantage, smart city development should also be designed in accordance with its natural characteristics and potentials.	ASEAN Smart Cities Network, 2018
Smart cities enable not only just smarter things but also smarter decisions. A smart city uses advancements in technologies to promote better decision-making for city officials, and their residents.	British Standards Institutions
A smart city is a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and businesses.	European Commission
A city is a complex system. Its complexity is due to the individuals’ unpredictable interrelations. As complex systems, cities have unpredictable behaviours. The concept of smart city frequently refers to the use of information and communication technology (ICT), as well as its implications on human capital/education, social and relational capital, and environmental concerns.	Lombardi et al., 2012
Smart cities are complex and dynamic socio-technical systems, a conceptualization without which “smart cities” – i. e., the penetration of cities by the information and communication technologies (a phenomenon also called digitalization) – cannot really be understood.	Finger & Razaghi, 2017
Cities are conceptualized as complex socio-technical systems – of – systems by emphasising holistic manner due to its social and technical interdependencies among dynamic smart city dimensions.	Geldenhuys et al., 2018

Different approaches of the actors who directly or indirectly play a role in the development process of the smart city concept are observed. Kozlowski et al. (2021, p. 517) conducted extensive research in literature and case study studies and concluded that the reason for this divergent conceptualization and definition approaches is because of “[…] the interest of urban authorities, communities, public institutions, and business in the smart city is observable in many cities, regardless of their size, geographical location, or cultural environment. However, the smart solutions they implement are not the same. This is due to cultural diversity, social awareness, investment in the research sector and the level of socio-economic development of country/region/city, correlated with available resources, which can be allocated in smart city areas.”.

These different definitions and conceptualizations were divided into four-types (Echebarria et al., 2021; Kozlowski & Suwar, 2021, p. 510–512; Singh et al., 2022):

“Techno-centricity” definitions aim to connect the city to technology (technological orientation).

“Human-centricity” refers to the importance of education, learning, and knowledge in driving urban development (human orientation).

“Organization-centricity” definitions focus on improving environmental, social, and economic circumstances to achieve their strategies aiming to increase their attractiveness and competitiveness through various projects.

“Hybrid” definitions integrate the technological, human, and institutional-organizational aspects of smart cities.

From this point of view, when the definition examples given above table are re-examined, it can be observed that Nokia and IBM, which offer smart city system technologies and operational platforms and business solutions, are techno-centric, while European Commission or research institutions such as the Demos Helsinki are in a hybrid definition approach.

Additionally, Toli & Murtagh (2020) reviewed 43 smart city definitions and evaluated them based on sustainability – and – non-sustainability orientation on environmental, economic, and social factors. According to their findings, sustainability-oriented definitions highlight the integration of human and social capital with physical infrastructure to create a liveable city. Non-sustainability-oriented definitions emphasize ICT's ability to make cities more connected, smart, and liveable. Subsequently, to fill this gap they proposed:

Long-run sustainability of smart city planning can be evaluated by the general theory of sustainable development with selected economic, social, and environmental sustainability indicators (See, (Luukkanen et al., 2024)

In addition to these five types of definitions, the integrative literature study carried out within the scope of the report revealed a "meta-definition" synthesis putting forward the holistic definition and conceptualization of smart cities (Kitchin, 2022; Yigitcanlar et al., 2018). This meta definition, which emerged based on the literature review, is a "holistic systems-thinking". It appears that throughout the progress of smart city development, conceptualization approaches have evolved from techno-centricity in 2000s to current cyber-physical systems-thinking. Consequently, the meta-definition of smart city can be conceptualized as "complex and dynamic socio-technical systems of systems" (Geldenhuys et al., 2018).

Sustainability-oriented definition

"Smart city is a concept of urban transformation that should aim to achieve a more environmentally sustainable city with a higher quality of life, that offers opportunities for economic growth for all its citizens, but with respect to the particularities of each locality and its existing inhabitants. This transformation is currently enabled by various types of technologies, typically provided by global industrial partners, that are embedded into the city's infrastructure system, transforming the existing provision of services by adding layers of interconnectedness."

(Toli & Murtagh, 2020, p. 8)

Dimensions of Smart City Assessment

Although there is no universally accepted definition of smart cities, as a result of the effort to fill research gaps in cities' smartness assessments, and to what extent the notion of smart city could be understood encouraged various scholars and generally accepted six smart city dimensions have been revealed (See Table 2): economy, environment, mobility, people, governance, and living conditions (Batty et al., 2012; Caragliu et al., 2011; Giffinger et al., 2007; Lombardi et al., 2012). It is noteworthy that cities are adapting their systemic aspects, notably with ICTs, in response to the challenges they are facing. For example, climate change stresses are gradually influencing various aspects of smart dimensions, such as environmental and ecological sustainability and governance frameworks, increasing systemic interconnection. These factors are based on regional competitiveness, mobility and ICT system integration, natural resource management, human and social capital, quality of life, and civic involvement in municipal government (Kozlowski & Suwar, 2021; Lombardi et al., 2012).

Table 2. *Smart City Dimensions and Explanations (Batty et al., 2012; Caragliu et al., 2011; Giffinger et al., 2007; Lombardi et al., 2012).*

Dimensions	Explanation
Smart Economy	It refers to a city's competitiveness, with an emphasis on elements such as innovation, entrepreneurship, productivity, labour market flexibility, and integration with the global economy. This entails using information and communication technology (ICT) to enhance e-business, e-commerce, innovation opportunities, manufacturing, service delivery, and the development of new products, services, and adaptive business models.
Smart Environment	The management of urban natural ecosystems, resource sustainability, biodiversity, and environmental preservation via Built Information Models - BIMs. Examples include effective waste management, the use of renewable energy sources, and environmentally conscious urban design, all of which use ICTs to improve the city's sustainable ecological and environmental processes.
Smart Mobility	Emphasizing sustainability, efficiency, and inclusion via utilizing new technologies such for city mobility services (e.g., autonomous public mobility, ridesharing), micro-mobility solutions, and integrated multimodal transportation networks. Cutting-edge ICTs is vital to enhance transportation infrastructure and supply commuters with real-time data and strive to cut carbon emissions, relieve traffic congestion, and improve the entire urban travel experience by combining technological developments and new policy efforts.
Smart Governance	Effective and efficient public administration, high-quality digital real-time public services, and citizen participation in decision-making processes. ICTs promote e-administration by assisting with decision-making, data-management, democracy, and service delivery.
Smart Living	Focuses on numerous elements of quality of life, with local authorities using ICT into daily operations to improve inhabitants' health, safety, culture, and general living circumstances.
Smart People	Emphasises citizens' education, social connections, and global openness, allowing integration, involvement in public life, and innovation by providing ICT-enabled access to education, training, and creativity.

Neirotti et al. (2014)'s study investigates the spread of smart city initiatives by comparing the dimensions covered by a city's best practices to the entire number of prospective domains. The study creates a taxonomy of applicable application domains, dividing them into three domains:

- **Hard Domains** (Smart Environment, Smart Economy, and Smart Mobility) involve infrastructure and resource management and rely primarily on ICT systems and urban design to increase sustainability, and
- **Soft Domains** (Smart People, Smart Living and Smart Governance) focus on social and cultural factors. Soft domains focus public interventions, human centricity, and sociocultural circumstances to promote sectors such as education, innovation, and social inclusion as part of smart city projects.
- **Hybrid Domains**, such as healthcare and public safety, require smart city initiatives that combine ICT deployment with policy interventions to improve services and efficiency.

The development of future smart cities is dependent on the interconnection and interdependence of hard and soft domains, which include six essential dimensions: Smart Economy, Smart Environment, Smart Mobility, Smart Governance, Smart Living, and Smart People. For example, Yigitcanlar et al. (2018) emphasize the need of having a thorough grasp of these dimensions and how they relate to desired objectives such as productivity, sustainability, accessibility, well-being, and the quality of life. Similarly, Finger & Razaghi (2017) underline the crucial role of technology in driving smart city development, as well as the significance of determining whether technological developments are motivated by public/citizen demand or technological push. Furthermore, Hollands (2008) underlines the need of human involvement in smart city initiatives, arguing that technology alone cannot designate a city as smart without considering the contributions of its citizens' needs.

Complex nature of urbanisation and city systems necessitates a holistic approach on effectively coordinating hard and soft domains in urban technology, governance frameworks, and risk assessment in smart city development (Batty et al., 2012). In this sense, e.g., Albino et al. (2015) and Caragliu et al. (2011) emphasize the relevance of both hard and soft domains in urban performance, stressing the rising importance of human and social capital in addition to conventional physical technology infrastructure – into future technological advancements essential for smart cities, including Artificial Intelligence – AI, deep learning, Internet of Things – IoTs, big data, and cybersecurity (Javed et al., 2022). Furthermore, Kitchin (2022) underlines the significance of supporting modal changes on soft domains toward sustainable smart mobility initiative's options "[...] An intelligent transport system that seek to optimize traffic flow is not going to resolve congestion; it requires shifting people from cars to public transit, cycling and walking." (ibid, 158). Thus, it is vital to emphasise the need of hands-on involvement and collaboration between public, private, research institutions, and people in constructing smart city frameworks built on both hard and soft domains including investing in high-tech infrastructure, human capital, and forward-thinking knowledge and strategy generation. Integrating these understandings is critical for promoting resilient future smart city developments meeting cities and its dwellers' current and future needs.

Pillars for Smart City Strategies

According to Kozlowski et al. (2021), the development of smart cities (SC) is closely linked to several local contextual elements. A city's smart city strategy and digital trajectory are greatly influenced by variables including population density, geographic location, urban structure, and economic growth. Albino et al. (2015) and Neirotti et al. (2014) also underline the fact that cities have different priorities and visions when it comes to accomplishing their smart city objectives, which highlights the diversity of smart city development strategies. Furthermore, demonstrating the complex nature of SC projects, Yigitcanlar et al. (2018) identify three main drivers: community, technology, and policy. These main drivers are connected to desired objectives including productivity, sustainability, accessibility, well-being, and governance.

As Javed et al. (2022) point out, technological improvements are causing a number of pillars to emerge in the landscape of SC growth plans. These include blockchain, big data, robots, smart transportation systems, deep learning, machine learning, internet of things (IoT), Digital Twins (DTs) and sustainable practices including electric and autonomous vehicles and product recycling. According to Cathelat (2019), when smart city strategies develop, they show a tendency toward maturity by including their own visions and related frameworks. Examples like "Aviapolis (Airport) City" (Ibid) and "Smart Port City" (Meyer et al., 2024; Turku's *Smart Port City Project*) highlight how cities customize their smart city strategies to take advantage of already-existing infrastructure, such ports or airports, exhibiting creativity and agility in response to possibilities and requirements specific to their community.

As the progressive growth process of smart city concept starts to achieve maturity levels across varied contexts, numerous new pillars in smart city development strategies are recognized. New trends indicate that smart city strategies could once again change. It was observed that cities' demographic patterns and growth visions are also starting to incorporate into smart city policies, as seen in the examples, Smart and – "[...] Aviapolis (Airport) City, Organic City, Eco City, Entrepreneur City, Innovative City [...]" provided by Cathelat (2019) and "Sustainable City' trends in Toli & Murtagh (2020). For example, a city with an airport may have examples such as "Aviapolis (Airport) City," while a city with a port could have examples such as "Smart Port City."

The Covid-19 pandemic, one of the wicked challenges in recent times, hastened the smart city strategy innovations, implementation roadmaps, and trends – including changes brought on by the COVID-19 pandemic – in an effort to better comprehend this transition (Boulanger, 2022). The dynamic character of smart city development in response to global concerns by suggesting that the pandemic may have speeded advanced technology integration in city systems. Subsequently, novel concepts like the "digital twin", "15-minute city," and "metaverse city" initiatives have been accelerated and got attention in smart city strategies, indicating a push for continual innovation and more digitization while prioritizing human well-being (Ibid).

Ranking and Standardization Approaches to Smart City Assessments

Numerous initiatives and studies aiming at mapping, assessing, and ranking cities based on six smart city dimensions used a variety of Key Performance Indicators (KPIs) and categorisations (Benamrou et al., 2016). For example, Giffinger et al. (2007) focused on 77 European cities having at least one university, generally medium-sized cities with populations ranging from 100,000 to 500,000 people, and utilized 34 standards and 74 indicators to benchmark and rank these cities. This first comprehensive ranking and assessing study had sensational impact in the field of academia and smart city domain. Notably, while some cities from Poland and Lithuania were included ranking and assessments, Turku, Tampere, and Oulu from Finland ranked among these cities. European Parliament (2014) carried out a Mapping Smart City study focusing on European cities, identifying 468 cities with populations greater than 100,000 and categorizing them based on six dimensions and maturity phases (133 in total) of smart city initiatives aligned with the European 2020 strategy.

Another world-wide stimulating work was conducted by Boyd Cohen (Cohen, 2014). Boyd Cohen introduced the Smart City Wheel, which targets cities worldwide and selects 120 eligible cities for benchmarking based on six dimensions, 18 factors, and 62 indicators drawn from an aggregate of 400, with the goal of ranking and benchmarking cities based on their smart city initiatives and progress (Cohen, 2012, 2013, 2014).

These initiatives contribute to a complete knowledge of smart city development and provide useful tools for policymakers, academics, and urban planners seeking to create sustainable and creative urban settings.

Recently, scholars, international organizations and institutions have introduced, more comprehensive indicators and categories, besides some organizations even publish annual rankings in various categories. As if a response to previous critical approaches on labelling and an understanding of transparency in smart city performance developments, the use of these standards and KPIs among cities become a “trend” (Huovila et al., 2019). Also, Kristiningrum et al. (2021) propose that standards be used as a common language to promote the creation and evaluation of smart cities.

ISO, the International Organization for Standardization, has a set of international standards aimed at sustainable development of communities aligning with SDGs, including indicators for city services and quality of life (ISO 37120:2018, 2018), smart cities (ISO 37122:2019), and resilient cities (ISO 37123:2019) (See Figure 1). These standardized indicators provide a holistic framework for monitoring and assessing numerous aspects of cities (World Council on City Data). They intend to make monitoring progress easier, promote mutual learning across cities, and help in policy creation and decision-making. The objective is to ensure that cities approach development holistically, considering present resource utilization and efficiency to properly prepare for future needs.

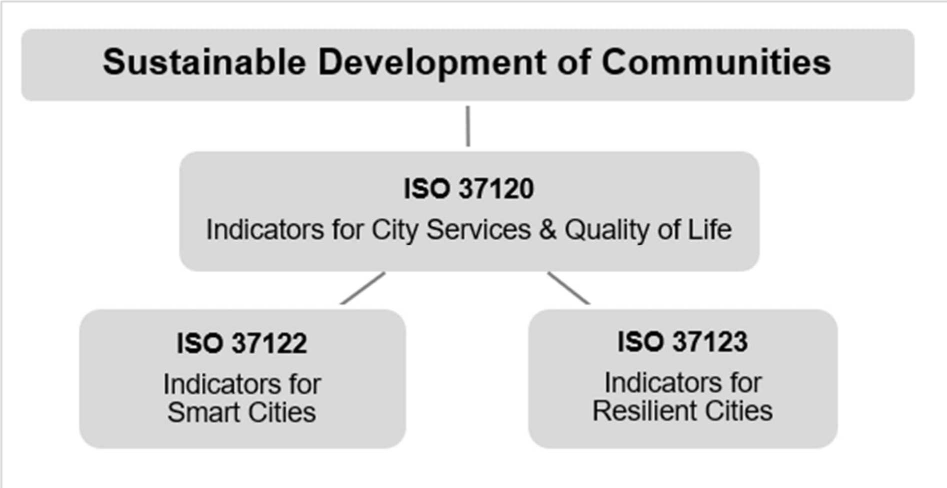

Figure 1. *Sustainable development of communities – Relationship between the family of city indicators standards (ISO 37120:2018).*

ISO 37120 (2018) Sustainable Cities and Communities – Indicators for City Services and Quality of Life, includes 19 categories and 111 indicators. These adjusted indicators (originally published in 2014) address a wide variety of issues critical to measuring the sustainability and liveability of cities. They include indicators for governance, economy, environment, transportation, energy, water, waste management, health, education, safety, culture, recreation, and more. There are two key observations related to ISO 37120:2018 standards. First, Gdańsk was reported the only city holding ISO37120 certificate compared to Turku, Vilnius, and Wrocław subject to this report. The second important point is that Boyd Cohen released a new version of the Smart City Wheel, adding critical KPIs of ISO37120:2014 (V.01).

ISO 37122 (2019) Sustainable cities and communities – Indicators for smart cities, used in conjunction with ISO 37120, assists cities in selecting indicators for implementing city management systems as well as carrying out smart city policies and initiatives. This includes 19 domains and 80 KPIs addressing challenges such as climate change and urbanization via more community participation, collaborative leadership, and the use of data and technology to improve services and quality of life. Its goal is to build a smart environment in which policies and technology serve residents, promote sustainability, reinvent infrastructure, stimulate economic growth, and prepare for future difficulties. It should be noted that the researchers used ISO 37122:2019 KPIs as the main basis for measuring the "smart city maturity levels" (Santana et al., 2018).

ISO 37123 (2019) Sustainable cities and communities – Indicators for resilient cities, consists of 19 domains and 77 KPIs and clearly defines what resilient city is.

Resilient City is:

"[…] able to prepare for, recover from and adapt to shocks and stresses. Cities are increasingly confronted by shocks, including extreme natural or human-made events which result in loss of life and injury, material, economic, and/or environmental losses, and impacts."

“[…] able to recover from shocks and stresses in a timely and efficient manner, with a focus on ensuring the continuity or rapid restoration of city services such as electricity, water, telecommunications, waste management, sanitation, food distribution, financial services and access to emergency services.”

“[…] a city that understands the necessity to adapt its systems and processes to ensure that they are as robust as possible in the face of shocks and stresses, building back better following extreme events, while focusing on the goal of restoring and ensuring long-term prosperity.”

Those indicators serve to the smart cites for being prepared to future shocks by acquiring a thorough understanding of its threats, reducing uncertainty and anticipate through proactive strategies and actions, and increasing awareness and involvement among people, public and private stakeholders, and academia.

Finally, the International Institution for Management Development (IMD) Smart City Index 2023 (IMD Smart City Index, 2023) evaluates cities throughout the world based on inhabitants' perceptions and expectations of and from their city's infrastructure and technology offerings. Compared to other KPIs, standards such as ISO, and benchmarking frameworks Boyd Cohen Smart City Wheel, the IMD Smart City Index examines inhabitants' perceptions/expectations. The assessment is divided into two sections: Structures, which examines existing infrastructure (city systems), and Technology, which evaluates technological services accessible to citizens. Each pillar is assessed in five major categories: health and safety, mobility, activities, opportunities, and governance. Cities are categorized according to their Human Development Index (HDI) ratings, and each category is assigned a rating ranging from AAA to D. Further only the Vilnius was reported compared among other 3 cities but as a reminder IMD Smart City Index 2023 utilizes strict inclusion criterion such as being capital city as Vilnius is capital city of Lithuania.

Amidst prevailing various standardization and assessment tools, it seems that they address various system structures of cities such as quality management and assessment of services and ICT infrastructure as well as quality of liveability. It was, however, noted that there are also standardization roadmaps. For instance, Wang et al., (2022, p. 419) proposed “Framework of Smart Sustainable City Standards Roadmap” based on national and international standards. Evidently, quality of city planning relates to the identification and application to the relevant standards (Abdi & Shahbazitabar, 2020).

2.2. Smart City Digital Twins

Digital Twins

Digital twins, which were originally developed by NASA engineers during the Apollo 13 mission in the 1970s (Grieves & Vickers, 2017), have proliferated alongside Industry 4.0 (Raes et al., 2022) with applications in a variety of sectors including health, aviation, and government (Deren et al., 2021) and recently they have become increasingly important in smart cities as a result of IoT, advanced technologies such as IoT, Geographic Information Systems – GIS tools, AI and VR, and the use of 3-D modelling (Kaivo-oja et al., 2020a, Kaivo-oja et al. 2020b; Zheng et al., 2019).

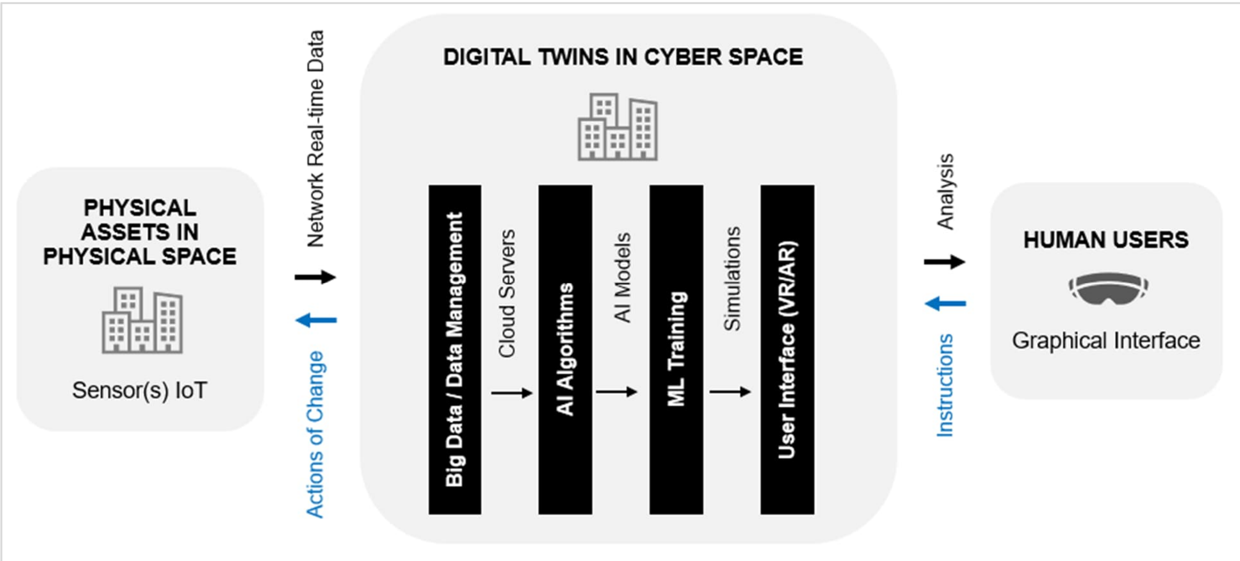

***Figure 2**. Digital Twin (Sources: Grieves, 2014; Neethirajan & Kemp, 2021).*

A digital twin is a "virtual representation of what has been produced." (Grieves, 2014, p. 1). According to White et al (2021, p. 1), digital twin is "a digital representation of a physical process, person, place, system, or device.". Further, Zheng et al. (2019) distinguished between narrow and wide definitions. The narrow digital twin contains virtual information that fully represents a physical thing, whereas a broad digital twin combines virtual and physical spaces, functioning as a Cyber-Physical System (CPS) capable of simulation, monitoring, computation, organization, and control (Ibid).

Regardless of the application domain such as city, aviation or industrial areas, digital twins are built up of three major components: a) actual entities in real/physical space, b) virtual/digital representations, and c) data and information links that connect virtual and real environments (Grieves, 2014).

Despite changing conceptual understanding of digital twins, misconceptions exist, particularly due to lack of Cyber-Physical Systems (CPSs) approach (Möller, 2016), and disregarding data flow characteristics between virtual and physical objects/entities (Deren et al., 2021; Fuller et al., 2020). Ferré-Bigorra et al. (2022) attribute this to the early adoption stage and insufficient literature particularly smart city domain, as seen by the widespread usage of the term "urban digital twin" often to describe simple 3D city models. While digital twins differ across domains and fields, they always have one essential characteristic: the characteristics of data flow in their operation whether they are manually adjusted, unidirectionally exchanged or bidirectionally automated.

Fuller et al. (2020, p. 2) briefly illustrate the differences (see Figure 3).

- Digital model is a digital representation of a physical entity that lacks autonomous data interchange.
- Digital shadow has a unidirectional (one-way) data transfer from physical to digital platform and data can be transferred in real-time.
- Digital twin is a completed system integrated real-time bidirectional data flow between a physical entity and its digital representation, with any modifications in both, affecting each other.

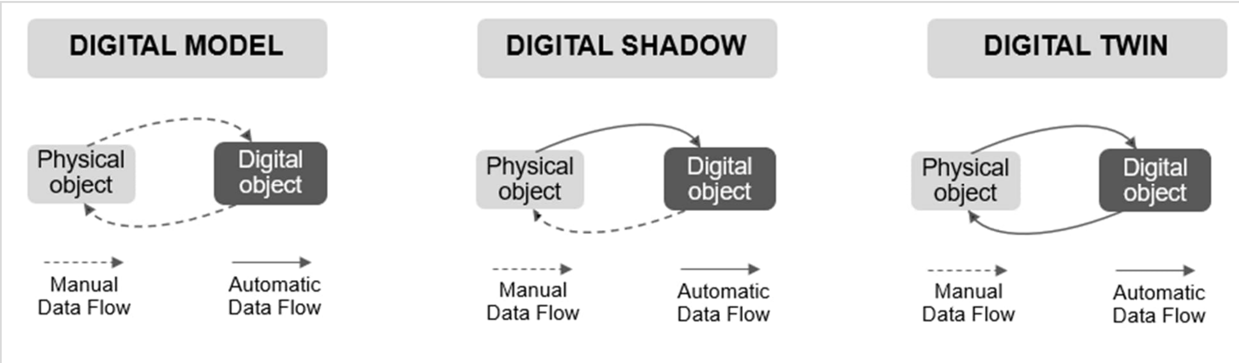

Figure 3. *Digital Model, Digital Shadow, and Digital Twin (Fuller et al. 2020, p. 3) Copyright by the authors. Licensee IEEE Access. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).*

Digital twins provide capabilities for planning future scenarios, acquiring insights through predictive and What-IF analysis derived by real-time data from physical entities, and enabling informed judgments or modifications to future-oriented policies (Deng et al., 2021; White et al., 2021). Recognizing the significance of digital twins in the global data economy, countries such as China, the United States, and the United Kingdom have created national digital twin working groups during the last decade to promote economic dynamics (WEF, 2022). Initiatives such as the UK's National Digital Twin Programme, led by the Centre for Digital Built Britain (CDBB), have pushed substantial study into digital twin capabilities after 5 years of DT development research and revealed 5-level of DT capabilities: Descriptive, Informative, Predictive, Prescriptive and Cognitive, from low to high maturity level respectively (See Table 3)[1] (CDBB, 2021).

Table 3. *Digital Twin Capabilities in the context of Smart Cities and Smart Mobility Exemplification with Possible Enabling Technologies (Modified from CDBB, 2021; Lu et al., 2019; Qi et al., 2021)*

Capability	Description	Key Question	Example	Enabling Technologies
Descriptive	The descriptive capacity entails gathering and displaying data to better understand dynamics. Tasks include conveying design and construction data, verifying information, securely managing the flow of data, and dynamic data aggregation. Interoperability, data quality, standards, format consistency, and update frequency are all factors to consider, potentially with Application Programming Interfaces (APIs).	**"What is happening?"**	To better understand current congestion patterns, real-time data on traffic flow in a smart mobility dimension is gathered.	Intelligent Traffic Management Systems capture real-time traffic data at important intersections and roads using smart sensors, CCTVs, and IoT devices. This data is processed by cloud-based technologies, and analytics and machine learning algorithms show congestion patterns. Strong communication networks, such as 5G or specialised IoT networks, allow for continuous data transfer. GIS and mapping technologies are used to visualise and analyse traffic flow data on a geographical scale.
Informative	The process of evaluating data to determine why certain occurrences occur is known as informative capacity. It is based on cutting-edge digital analytics approaches that consider data quality, completeness, and consistency, as well as assuring trust and legal compliance with ownership of data and source.	**Why did it happen?**	Examining past data on traffic flow, weather patterns, and public transit schedules to pinpoint the reasons behind congestion and delays in a particular zone.	Big data analytics, IoT devices, GPS tracking, traffic sensors, weather monitoring systems, and historical transportation data are used to analyse and discover trends in the smart mobility disturbances. It helps city planners and transport authorities to make informed choices and put measures in place to reduce congestion, improve traffic flow, and improve smart mobility solutions.
Predictive	Predictive capacity relies on real-time monitoring and data science to estimate future events and outcomes using machine learning. While prior phases' concerns are still significant, additional criteria include predictive process fit for the given scenario analysis and the mainstream acceptance of predictive analytics.	**What will happen?**	Historical data and machine learning algorithms are used to forecast traffic congestion patterns during peak commute hours, allowing for proactive management.	Sensors, GPS devices, and traffic cameras. Machine learning algorithms use sophisticated methods such as neural networks or decision trees to search for trends in past traffic data. Real-time data from sources such as traffic sensors, connected vehicles, and mobile applications improve forecast accuracy. Cloud computing manages vast amounts of data and complicated computations for predictive analytics. IoT devices such as traffic sensors, smart cameras, and connected vehicles continually collect real-time data for prediction models.

[1] Since the scope of the report is the Smart City Digital Twins, to make the digital twin more comprehensible to the reader, an exemplification in the dimension of Smart Mobility has also been provided.

Prescriptive	The prescriptive capacity extends beyond prediction to "recommend" interventions and actions to digital platform managers. It uses predictive modelling, optimization, and AI-based learning to find effective measures. Addressing bias in datasets, running "what-IF" scenarios, analysing results, and determining ownership of discoveries are all important considerations.	**What should I do?**	Predictive modelling, what-if scenarios, and optimization algorithms are used to deliver customized suggestions for advanced informed-decisions.	Advanced analytics: analyse massive datasets, predict traffic patterns, and optimise travellers travel experiences, artificial intelligence, machine learning. The system can adapt to changing situations and deliver effective and customised mobility solutions by combining real-time user data and continually upgrading the algorithms.
Cognitive	Cognitive ability facilitates independent acts by Digital Twin within defined constraints. It entails making predictions, learning from large datasets, and employing automation to operationalize data. Predictions can prompt automated actions, such as raising flood barriers or rerouting traffic. Scalability, effective integration of staff, procedures, and technology, and data management in operational contexts are all important factors to consider.	**What actions can be taken automatically?**	IoT sensors collect real-time data, optimizing through data analytics and machine learning. Automated control systems enable real-time autonomous DT adjustments to physical entity.	IoT Sensors: Collect real-time data on ambient light, weather, and pedestrian movement. Data Analytics: The use of advanced algorithms to process and analyse acquired data. Connectivity: 5/6G A reliable and fast network infrastructure that allows for continuous data transmission. Edge Computing: Processing and decision-making in real-time at the streetlight level. Control System: A centralised or distributed system that receives and processes data and initiates automatic changes. Machine Learning: Algorithms for continuous learning and lighting level modification.

Navigating the Nexus: Unveiling the Dynamic Realm of Smart City Digital Twins

Smart City Digital Twins can be defined narrowly as virtual representation of city systems; broadly as complex socio-technical Cyber-Physical Systems (CPSs) at where real-time data and autonomous actions are bidirectional between both physical and cyber entities. In ideal stage, SCDTs react simultaneously when action is required into the physical entity resulting in adjusting changes in both CPSs' sides.

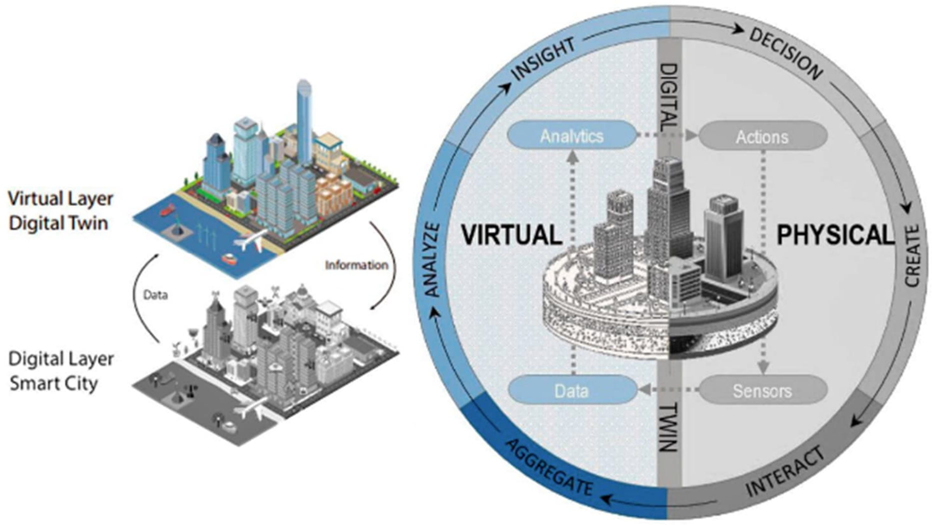

Figure 4. *Smart City Digital Twin (Caprari et al., 2022, p. 4) Copyright by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).*

The literature on digital twin practices in smart cities includes a variety of terminological usages. Mylonas et al. (2021) emphasises the need of treating digital twins as cyber-physical "systems of systems" in smart cities due to their distinct dimensions, complexity, and technical requirements. Nochta et al. (2021) and Qi et al. (2021) highlight considerable differences in the application methodologies and aims of digital twins in smart city systems, which are impacted by the unique technical and architectural features of diverse and complex physical city entities. However, Lehtola et al. (2022) debate that a techno-centric approach ignores human agency which limits the use of digital twins in smart cities. In contrast to industrial digital twins, which use physical entities to represent products or processes in virtual space – such as via digital platforms or VR in virtual platforms – including human agency into smart city digital twin systems poses privacy, security, ethical, and trust problems (Fuller et al., 2020), since humans act as both data providers and consumers.

Smart cities are socio-technical systems that involve a variety of stakeholders such as citizens as data providers and users, city officials, social organizations, complex enabling technology infra-architectures and industrial/business actors (Finger & Razaghi, 2017; Geldenhuys et al., 2018; Nochta et al., 2021). To manage the large and heterogeneous dynamics within the city systems, a shared knowledge base with extensive vocabularies needs to be established, according to Petrova-Antonova & Ilieva, (2021), using upper-level ontologies is essential to overcome difficulties such as data silos and semantic interoperability in smart city digital twin modelling. For example, "object" refers to physical entities, but "entity" includes structures, people, smart systems, and the entire city (Ibid). However, in industrial contexts, "object" usually refers to a product or production process (Grieves & Vickers, 2017). Thus, it is vital to comprehend and emphasize the need of developing shared ontology and standards, then initiate joint approaches on smart city digital twin schematics, technology architectures and policy designs.

Recent research highlights the crucial significance of digital twins in smart cities across a variety of disciplines. Alva et al. (2022) highlight application cases such city-scale forecasting, emergency planning, and operational optimization, whereas Deren et al. (2021) concentrate on smart grid services, traffic management, and public health (See Table 4).

Table 4. *Smart City Digital Twin Use Case Examples and Explanations (Karayel, 2023, p. 41–42).*

Use Case	Explanation	Resource
City-Level Forecasting	Smart cities can use digital twins to address difficulties arising from rapid urbanization, such as asset management, resource allocation, service maintenance, waste management. Digital twins provide advantageous data that may be shared at the district or municipal level, allowing urban management, planning, and associated agencies to make more informed decisions.	Alva et al., 2022
Emergency Planning	Using digital twins for emergency planning allows cities to develop rapid responses or contingency plans for severe events. These catastrophes might include natural disasters, healthcare problems, security concerns, or other potentially dangerous conditions impacting cities, dwellers, and ecological environment.	
Operational Optimisation	Digital twins can improve the operational efficiency of different urban systems and resources, including energy, mobility, the environment, communication, buildings, and infrastructure. They offer better performance management across these domains, resulting in higher operational efficiency via accurate real-time data.	
Participatory Planning	Urban planners and administrators can use digital twins to store, retrieve, compare, and analyse various dispersed sorts of city data. By this they can take coherent actions with informed decision-making considering all up-to-date real-time data from all systems of the city.	
Policy Development	By anticipating behaviour and responses to policy implementation and structural changes, digital twins can help to make planning more informed, efficient, and participative.	
Scenario Modelling – What-If Analysis	Digital twins for scenario modelling can allow for the evaluation of design alternatives and what-if analyses by properly reproducing real-world situations for virtual testing. Virtual scenario simulations generate vast data sets and statistical capacity to investigate different scenarios such as for complex transportation circumstances, including safety evaluations.	
Smart Grid Digital Twin Services	A simulation method that incorporates physical entities, temporal and geographical scales, and probability. It takes full advantage of the power system's physical model, virtual measurement data, and historical operation data. It depicts the whole life cycle of the smart grid in virtual space.	Deren et al., 2021

Smart City Traffic Brain	Digital twins can evaluate real-time traffic data and construct algorithms to analyse congestion and make informed judgments, considering past traffic, vehicle speed, and other relevant factors and data sets.	
Smart City Public Epidemic Service	Digital twins can create patient spatiotemporal data by merging hospital information with spatiotemporal trajectory data. Digital twins can detect epidemic outbreaks and individuals in close vicinity by utilizing artificial intelligence (AI) and machine learning (ML) for spatiotemporal proximity analysis. The findings may then be immediately sent to the response system component.	
Flood Monitoring and Flood Situation Services	Services have three major components: real-time flood data collecting via IoT, flood knowledge mapping, and flood service applications. It collects flood data from urban meteorological stations, ground sensors, and satellite remote sensing technologies to track river water status, rainfall, human/vehicle movements, and changes in water volume and level in rivers and reservoirs across wide areas.	

Mylonas et al. (2021) underlines the relevance of digital twins in solving urban challenges such as sustainability and health, and they also present a high-level overview of smart city digital twins (See Figure 5).

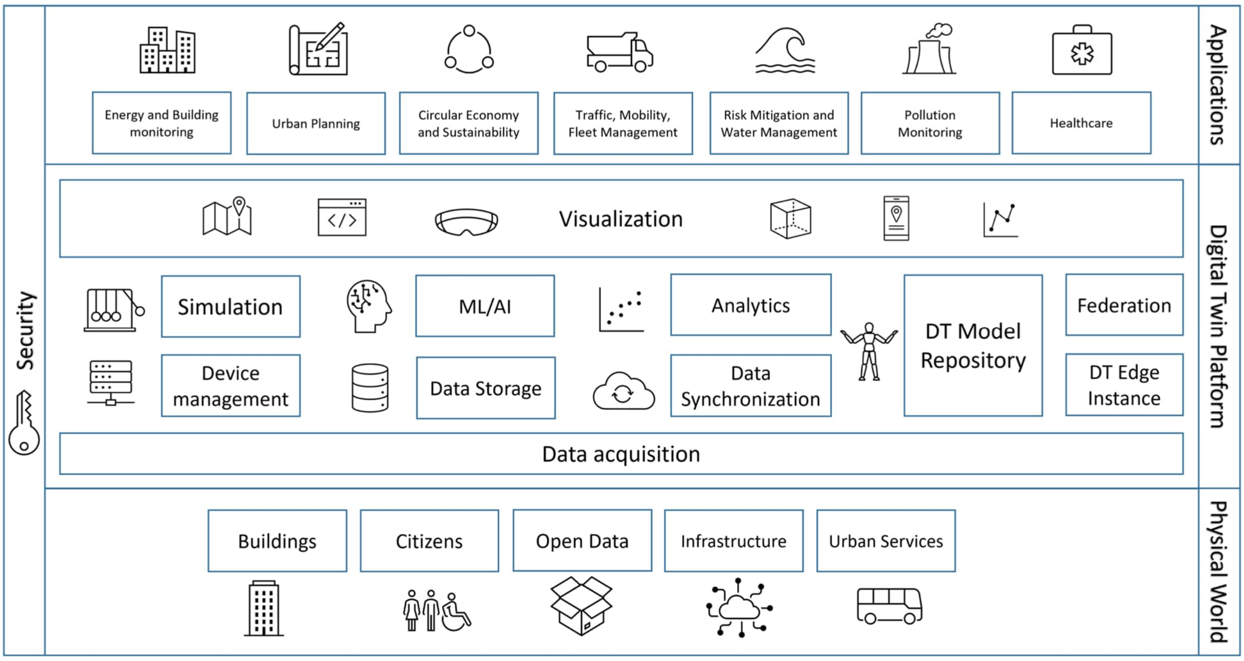

Figure 5. *High-level overview of city-scale DTs (Mylonas et al., 2021, p. 143229) Copyright by the authors. Licensee IEEE Access. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/).*

They provided a high-level overview of a city-scale DT in figure, including its primary components, real-world data sources, and key applications. Enabling data collection technologies such as IoT sensors, edge, and GIS send data from the physical world to the key components of a DT platform – whether what capability DT has, where it may be processed using enabling technologies like ML and AI and then simulations using models from the DT model repository. Outcomes can be conveyed to end-users or other systems using the available visualization components (e.g., Web portals, VR, 3D models, and maps), depending on the individual application domain, while cyber security covers the whole stack.

Policy and Sectoral Challenges

Digital twins have recently received a lot of interest, particularly in the field of smart cities. However, significant issues in terms of policy and sectoral significance were reported.

The Table 5 summarises significant policy-related issues. Short-termism, emphasized by Raes et al. (2022), highlights the challenge posed by efforts with immediate attempts and project and fund-based approaches. Misconceptions, as emphasized by Alva et al. (2022) and Fuller et al. (2020), cause confusion and impede scaling due to differing definitions and models. Other listed challenges including the requirement for an upper-level ontology to solve semantic interoperability and data consistency, and the lack of national and international policy standards were critical ones discovered during the research.

Table 5. *Summarized policy challenges related to future smart city digital twin initiatives (Karayel, 2023, p. 55–56).*

Policy Challenges	
Theme	**Explanation**
Short-termism	The prevalence of short-termism, linked with the reliance on project-based or fund-based periodic digital twin (DT) initiatives, poses a substantial impediment. (Raes et al., 2022)
Misconceptions	Divergent definitions, models, designs, and misconceptions have resulted in ambiguity and non-scalable implementations (Alva et al., 2022; Fuller et al., 2020)
Upper-level ontology	The building of an upper-level ontology should be a first step in implementing city-level DTs to address difficulties such as semantic interoperability, data consistency, and managing data complexity, quantities, and quality. (Mylonas et al., 2021; Petrova-Antonova & Ilieva, 2021)
Digital Twin Bureaucracy	Digital Twin Bureaucracy (DTB) is fundamentally different from e-government and smart governance because real-time engagement with the physical environment requires reorganization. (Eom, 2022)
Legal Responsibility	There is also the legal problem of who is accountable if the DT makes and/or suggest decision in a smart city by which ends with wicked circumstances. (Ferré-Bigorra et al., 2022).
National & International Policy Standardization	The importance of national and international standards in addressing issues related to data storage, cyber-security requirements, and allowing data exchange across varied APIs, geographical locations, and businesses. (Rasheed et al., 2020).
Multi-actor communication	To transcend communication obstacles between stakeholders, participants, a collaborative design technique are necessary. (Barricelli et al., 2019)

Socio-technical perspective in policy design	The socio-technical approach on SCDT development should be highlighted, considering high-level policy goals, local context, and the value of individual and organizational learning. (Nochta et al., 2021)
Vertical & Horizontal Interoperability in Local and National Level	A deficiency of vertical and horizontal interoperability among city departments and stakeholders results in redundant expenditures and infrastructure creation. As a result, cultivating a high-level design thinking and political savvy is critical to creating an integrated city strategy network. (Lu et al., 2019; Lv et al., 2022)
Local Context	A socio-technical approach is required to conceptualize, create, and execute SCDT system strategies as assemblages that reflect local contextual possibilities, priorities, and restrictions. (Nochta et al., 2021)
Citizen-centricity	An emerging focal point within the scholarly discourse is citizen-centric DTs. (Raes et al., 2022; White et al., 2021).

The continued Table 6 addresses the sectoral problems associated with integrating digital twins in urban settings. Scaling difficulties, such as those outlined by Lu et al. (2019), underline the need of prioritizing important technologies like open data platforms and APIs to avoid vendor lock-ins. With the old business models, as stated by Dignan (2020), IT enterprises aim to dominate the market, underlining the necessity for new adaptive business models. Further challenges including identifying the major stakeholders (citizens or customers) and addressing the absence of high-level systems thinking in urban planning were among critical challenges to be considered for overcoming obstacles in smart city digital twin development.

Table 6. *Sectoral Challenges on smart city digital twins (Karayel, 2023, p. 55–56).*

Sectoral Challenges	
Theme	**Explanation**
Scaling Issues	The prioritizing of essential technologies, particularly shared open data platforms and Application Programming Interfaces (APIs) are emphasised to be free of vendor lock-ins. (Lu et al., 2019)
Old Business Models	IT corporations have struggled to establish feasible and scalable solutions due to aiming dominance in the smart cities industry because they adhere to old business models with high return on investment (ROI) and a dependence on confidential solutions. (Dignan, 2020)
Citizens or Consumers	Local governmental agencies are the major promoters and users of DTs. (Ferré-Bigorra et al., 2022)
High-level systems thinking on city	A city is an open, complex, and large system. High-level system design and planning are lacking in scientific, rational, and accurate approaches. (Lv et al., 2022)
Local degrees of fidelities	A holistic city DT requires many local levels of authenticity. (Lehtola et al., 2022)
Quadruple Helix Cooperation	Cities should adapt their policy to promote more dynamic quadruple helix collaboration (working with stakeholders other than ICT giants, including academics,

	start-ups, and citizens), to prevent the risk of vendor lock-in and multinational corporations' dominance in smart city development. (Hämäläinen, 2021)
Common Feasible Architecture	Higher-level Connected DTs can optimize the performance of organizations and industries across borders, demanding a common architecture for efficient and reliable interaction throughout DTs. (Raes et al., 2022)
Sectoral Standards	The lack of data quality and management standardization and interoperability is a serious barrier, because only a small number of city level DTs can exchange data with other cities or organizations. (Ferré-Bigorra et al., 2022)

Considering those challenges, Lehtola et al. (2022) emphasizes the need of digital twin frameworks that match the city's fundamental needs, allow varying degrees of accuracy, enable real-time bidirectional data updates, and incorporate the human agency into decision-making processes. Similarly, Deng et al. (2021) provide a three-level framework, and White et al. (2021) present a six-layered approach.

Despite existing smart city digital twin initiatives there is still a shortage of consistent digital twin models for smart cities. It seems, it is due to plausible nature state of smart city digital twins. For example, according to Kozlowski & Suwar (2021, p. 517) it is due to “cultural diversity, social awareness, investment in the research sector and the level of socio-economic development of country/region/city, correlated with available resources, which can be allocated in smart city areas.". Further, different smart city strategies and digital twin development motivations are essential reasons – such as aiming of being Aviapolis (Airport) City, Organic City, Eco City, Entrepreneur City, Innovative City (Cathelat, 2019) or customized priorities based on city needs (Lehtola et al., 2022).

Thinking in terms of cyber-physical systems shapes the future of smart cities and promotes the integration of digital twin platforms and applications, Figure 6 depicts the fundamental layers. In Physical System, Layer 0 displays the city's geographical structure (does city has river, hills, channels? What is the underground soil structure? or does the city on the earthquake zone? whereas Layer 1 represents tangible elements including on and off the ground buildings, people, goods, ecology, airspace. Layer 2 includes all-infrastructure settings, ambient surrounds, and organizational (public-private-citizen) system structures. Layer 3 depicts the entire city as a socio-technical complex system, including components such as mobility, environmental and ecological conditions, government, human relationships, and services that affect daily living.

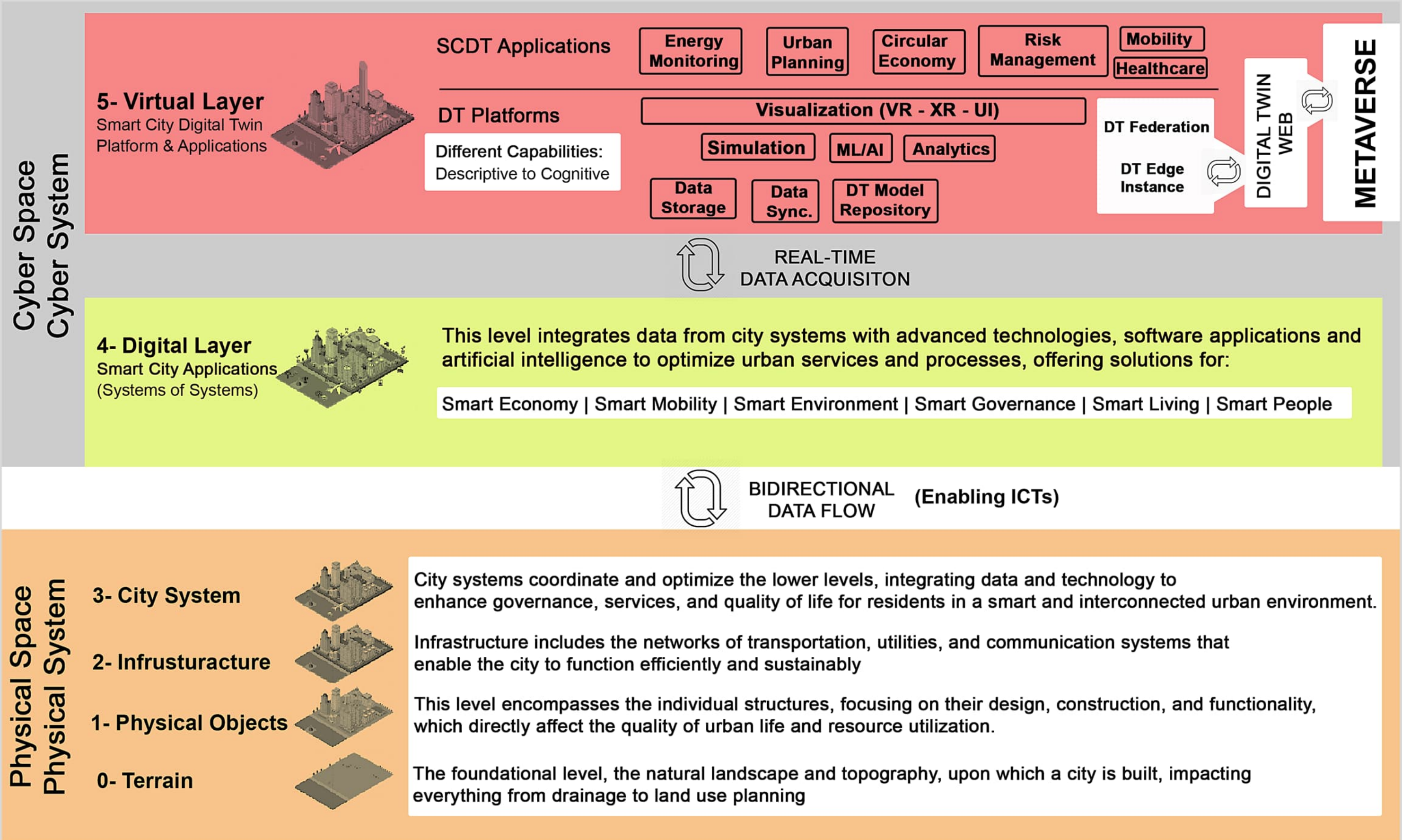

Figure 6. *Cyber-Physical Systems Thinking on Smart City Digital Twin development (Inspired from Autiosalo, 2021; Lu et al., 2019; Möller, 2016; Mylonas et al., 2021; White et al., 2021).*

The physical system in physical city settings is connected to cyber space/systems with bidirectional data flow and actions via enabling ICTs (IoTs, sensor technologies infra, CCTVs, GIS, ambient technologies, etc.). In cyber system, Layer 4 is the digital systems, which is linked smart city applications connected to physical city settings via enabling ICTs. The Layer 5 includes SCDT apps and platforms powered by real-time data from the fourth layer and enable bidirectional interchanges in real-time with physical city systems.

In addition to the various applications and platforms depicted in the fifth (virtual) layer, it is necessary to mention the SCDTs alignment to Digital Twin Web (Autiosalo, 2021) and then, Metaverse in the upper right corner. To achieve these alignments at the optimum level, the CPS structure should be complementary to each dimension (six smart city dimensions). This may have an impact on Digital Twins’ federated learning process since training and learning involve the exchange of extra information throughout the system hierarchy (Mylonas et al., 2021, p. 143243). However, Digital Twins assist in determining the best intelligence distribution across the far edge components, within the DTs. Autisalo (2021) introduced the Digital Twin Web (DTW), as a global network of digital twins. In the network, each digital twin is represented by a document. While DTW's structure is like the World Wide Web (WWW), the main distinctions are the direct connection to the physical world and readability for both people and machines (IoTs). However, as Autisalo (2021, p. 52) outlined, exploring the relationship and future paths between DTW and

Metaverse should be further researched possibly by utilizing Kaivo-oja (2017)'s participatory foresight research methodology in the context of SCDTs. In this study, we have applied the hybrid foresight approach discussed in the article of Myllylä and Kaivo-oja (2024). The Metaverse technology has a huge potential to transform citizen participation in smart city projects. Residents can provide feedback and actively participate in decision-making processes through virtual town halls and immersive city planning consultations in the real-time framework. This inclusive metaverse approach to governance surely promotes greater transparency and responsiveness in city planning (see e.g. Chen et al., 2024). In the future, it may be possible to integrate hybrid foresight methodology into an inclusive metaverse approach to urban planning.

Technological Preconditions for Smart City Digital Twins

In this section, we want to underline that planning data infrastructures, data spaces, and details of data management are strategic issues in the process of data economy development. These issues are strategic issues for city planners and decision-makers.

Standardised ways of collecting data and building reusable software blocks for digital twins always need the stored data. SCDTs usually require vast amounts of data in more efficient ways than silo-based vendor dependent storage. Smooth data communication is also of great importance (Hu, 2023), if one part does not perform then other parts will suffer. Silo-based storage is inefficient like silo-based software development: It is costly to maintain, update, and develop and this approach brings unnecessary hurdles when integrating systems.

One of the solutions for avoiding data storage silos is to build common Data Spaces (Data Space Business Alliance, 2024). According to the *Smart Cities World (*FIWARE Foundation, 2024) white paper there are three important factors:

1. Data interoperability: What are the protocols that participants will use in a data space for exchanging data? What is the vocabulary they will agree to ensure they understand each other, and create traceability in the exchange of data?

2. Data sovereignty and trust: A commonly agreed technology framework is required to ensure participants can trust that the organisations they exchange with are who they say they are, have agreed to the overall data space governance rules and have valid credentials. How can that trust be built, and the right level of identity management be achieved? What language for defining the policies for accessing data services and usage of data will be used, and what technology can be used to enforce those policies?

3. Data value creation: What technologies will participants use to describe their data services and offerings around those services, especially if these are to be monetised? How can these services be promoted and published, e.g. in data marketplaces?

4. Strategic questions: Do we need to define the above ourselves, or should we use defined ways of operating by using existing standards like ETSI NGSI-LD Wikipedia (2024) which defines the architecture and interoperability of dataspace communication? Should we use query languages like GraphQL (GraphQL, 2024) for extracting data from multiple sources via APIs? A successful SCDT will still need to describe data structures for various functionalities as well as utilize brokers acting as bridges within cities as well as between cities. Cities have existing historical SCDT and other data which is difficult and maybe not worthwhile to convert to a standardized modular format. This means that SCDTs will need data brokers.

Building modular SCDTs will require data security and identifying individual APIs, stakeholders, or partners. The W3C consortium has agreed on DIDs (Decentralized Identifiers) (The World Wide Web Consortium (W3C) 2022) that could (should) be used for this purpose. This is also, for most cities, a future development to be considered when defining new projects.

The value creation of the data must implement the European Union Data Act (European Commission, 2024) as well as other regulations. In other words, sharing and utilizing each other's data will require everyone to follow the regulations. Transparency and reliability for the exchange of data should be always secured which brings us to the question of who is responsible for monitoring the systems. The fear of sharing data between DTs, cities and other stakeholders can be avoided by using a system like Tritom from Data Space Europe (Tritom, 2024) compatible with European data economy operators, see GAIA-X (Gaia-X., 2024) and IDSA (IDSA 2024).

The design of a large SCDT requires knowledge and utilization of data-related standards on many levels as well as solid planning of the implementation of modular SCDTs. Also, case studies of cities can be helpful. For example, a very central urban city planning question is to plan city locations of sensors in smart cities (see Shah et al., 2019).

Thus, today many smart city and digital twin technological developments are ever-growing and yet more fragmented. The more holistic urban planning approaches are not widely applied. The reductionist mindset dominates strongly digital development and information system thinking. Holistic thinking is a rare treat in urban planning. Alongside inconsistent digital approaches and attitudes across the departments of city administrations, such developments have made it very difficult to reap all potential benefits of city digital twins (CDTs). In the ongoing pursuit for smarter cities with better liveability, the very rapid pace of isolated and siloed technological developments and their growing complexities (with serious pitfalls) have become too significant to ignore anymore by decision-makers in the business and public sectors. As a starting point for a more conscious engagement of practitioners and city planning professionals with SCDT development, the differences between semantic and *system-integrated city digital twins* need to be discussed and analysed more deeply. The conundrum of better interoperability and compatibility for smarter cities is much needed in the near future, especially in terms of what we can learn from existing CDTs and alternative novel urban planning approaches. Especially, strong claims of the promise of new CDTs as the next generation of urban development models in digital city planning and governance need very strong strategic attention from city planners and decision-makers of cities. When designed in the right ambient professional way, CDTs can cut across many existing data silos to enable cross-disciplinary and inter-sectoral collaborative processes. Cross-professional debate is important and necessary. These kinds of urban planning changes can also potentially promote public participation and stakeholder engagement. The current situation easily leads to "the bicycle" being reinvented repeatedly in fragmented and siloed systems. Data silos can be very costly for taxpayers (see e.g. Quek et al., 2023, 16). Of course, this kind of siloed urban development strategy is not very smart.

Secondly, in technical terms, the key bottleneck of CDTs today lies in poor interoperability and compatibility between the various technological approaches, digital solutions, and DTs. There is a great deal of complexity and lack of transparency built into IT systems. IT systems communicating with each other is often seen as impossible in practice. Today, existing trajectories of city planning, and governance processes are moving toward an ever-growing digital ecosystem of individual micro-solutions for transforming their workflows. This is a worrying development. It is anticipated that these technological developments will have profound consequences for jobs and decision-making in city governance, and not only positive consequences. Nevertheless, much of their ongoing developments remain fragmented, perpetuating an ever-growing heterogeneous, distributed, and dynamic digital ecosystem. It is difficult to get fragmented systems to serve citizens and taxpayers. The weak interoperability and compatibility between digital solutions, and consequently, CDTs, hinder the capacity to develop virtual representations that can replicate the immense complexity of urban systems to support city administrations. Moreover, such challenging bottlenecks prevent the deployment of a digital ecosystem framework that would deliver more value to citizens and communities. Failure to address bottleneck problems can easily lead to potential resource inefficiencies and reduced productivity in the delivery of urban services, which is strongly contrary to the objectives, visions and overall management practices of smart cities, which are central to the consensus-based urban planning processes.(Quek et al., 2023, 16).

There are some larger questions of integration. Such larger integration questions are the question of connecting smartly the indispensable roles of IoT and artificial intelligence in smart cities (see Chen et al., 2024; Nguyen et al., 2024). In principle, AI can greatly boost the expected SCDT development in smart cities.

IoT and AI integration: Impacts on planning data spaces and data management

Today, the pace of societal development is today faster than ever before, and the smart city paradigm has emerged. This novel city development paradigm aims to enable citizens to live in more sustainable cities that guarantee well-being and a comfortable living environment. This big and board urban change process has been done by a network of new Industry 4.0 technologies hosted in real time to track the activities and provide smart solutions for the incoming requests or emerging practical urban living problems of the citizens. One of the most often used technological methodologies for creating a smart city is the Internet of Things (IoT), so-called "umbrella" technology. The IoT-enabled smart city research programme consisting of many different urban planning domains such as transportation and mobility, healthcare, social services, education, finance and taxation, and agriculture, has recently attracted increasing public attention in the global research community. Further, today we know that advances in artificial intelligence (AI) significantly contribute to the growth of IoT. The definitions of the smart city concept, the background of smart city development, and the components of the IoT-based smart city must be defined carefully (see Chen et al., 2024; Nguyen et al., 2024).

Key fields of AI developments are: (1) Machine learning, (2) natural language processing and (3) image vision. Key fields of machine learning are supervised learning, unsupervised learning, reinforcement learning and deep learning. Key field of natural language processing are tokenization, entity recognition, sentiment analysis and machine translation and speech recognition. Key fields of image vision are object detection, facial recognition, image segmentation and pose estimation. All these AI tech fields provide new solutions for SCDT developments. (see e.g. Santonen &

Kaivo-oja, 2023, 2024). Key SCDT development areas in relation AI key fields are human learning processes, human communication processes, and human smart behaviours and decision-making.

Big data analytics: Impacts on planning data spaces and data management

Huge research efforts have been made to develop efficient distributed big data processing models operating on heterogeneous technical devices. More investigations should be conducted in different stages of data processing. For example, to reduce the cost and latency in the data storage stage, we can process the streaming data at the network's edge using fog computing instead of transmitting all the data to the central node. Further, many parallel computing models such as MapReduce framework, FPGA programming, and GPU processors can be employed to process the data gathered from multi-source in a distributed manner. However, there are still many flaws in the current research works, which require the extension to be well adopted in real-time estimation. For the analysis models, the fast-paced development of AI brings many potential works in the technical fields of AI-based learning, AI-based language processing, and AI-based computer vision. These include the development of AI-driven advanced techniques for better data fusion which can extract meaningful hidden patterns from multi-source data collected from smart cities. Multi-source data systems can also be linked to the systemic logic of Smart City Wheel. Efficient data reduction and feature selection methods can ensure the removal of data redundancy. Regarding the predictive algorithm, explainable ML and DL algorithms are more in favour of rather than conventional ML and DL counterparts. Further, data drift should be considered to ensure that the developed models fit well with the continuous data change. Techniques such as incremental learning or online learning should be extended for this purpose. All AI-based learning algorithms (supervised learning, unsupervised learning, reinforcement learning, and deep learning) can be useful in smart city development (Santonen & Kaivo-oja 2023, Santonen & Kaivo-oja 2024). The key issues in the integration of IoT and AI technologies are (1) Security and privacy, (2) Priority components, and (3) Smart city awareness (see Nguyen et al., 2024).

A recent survey by Abadia (Peralta Abadía et al., 2022), revealed that (1) sustainable IoT technologies have only been reported in a few IoT frameworks, (2) less than half of the IoT frameworks target interoperability and scalability and (3) security has been addressed using authentication, but encryption is lacking. These findings indicate the importance of professionally planned data infrastructures in the field of smart city digital twins. Special attention should be paid to *information diffusion across cyber-physical-social systems (CPSS)* in smart cities (see Zhou et al., 2021). For example, if we want to develop more sustainable traffic and mobility services, we must plan how data mining and machine learning apps actually support sustainable mobility in a smart city (See Shafiq et al., 2020).

There are three major challenges to consider:

1. Security and privacy. There are various research areas to strengthen IoT data security and privacy in smart cities (i.e., encryption/decryption algorithms, authorization technologies, and data anonymization tools). The most noteworthy advance, blockchain technology, is designed to support *the execution of security techniques.* In the smart city development domain, blockchain has been advocated to safeguard and protect the application environment by employing a decentralized architecture for the system design of smart cities. Smart contracts on the blockchain are very promising cybersecurity solutions. However, these critical research areas are not sufficiently addressed in current research works. in the future, given information-centric smart cities consisting of many components, more *studies focusing on blockchain* could help to allow a more secure environment and enable smarter interconnection between the different components (Nguyen et al. 2024, Chapter 5).

2. Priority components. Some smart city components are expected to be more focused in the future. Smart energy (i.e., smart energy, green energy, and sustainable energy) is critical in building a sustainable environment and a strong foundation for implementing smart cities. Smart healthcare is another priority topic that has attracted a lot of attention as the demand for a more convenient healthcare service management and accurate disease diagnosis, the use of a smart healthcare system that reduces medical costs and responds to medical conditions is further reinforced by many different advanced technologies such as AI-based. More convenient and comfortable living can be made possible by the services provided by smart healthcare systems (SHSs). (see Nguyen et al. 2024, Chapter 5). Also, all educational and learning aspects of smart cities need more attention in smart cities.

3. Smart city awareness. More political and communication efforts should be put into encouraging the citizens' engagement in a smart city. As the smart city network has expanded recently, the citizens may not always be comprehensively aware of the provided SC services and SC applications. As a part of smart cities, the citizens also play an indispensable role in the success of smart cities, especially in the planning and implementation of huge management processes of smart city digital twins. If the citizens are educated and informed properly about the SCDT concept, they may recognize various potential advantages and benefits of smart city projects and services. Also, some city services can be cheaper in the future, if SC solutions decrease the costs of city services. As a result, they may be more responsive in providing useful input and feedback for service outcomes and service quality. This kind of consumer and citizen feedback would allow the government and developers to be more aware of their needs and opinions, directly adjusting the services' development (see Nguyen et al. 2024, Chapter 5).

Metaverse and smart city development: Impacts on data spaces and data management

The concept of a smart city is geared towards enhancing convenience and the efficient management of city areas through technical, social, and business model innovations. As Metaverse development rises in the 2020s, providing the possible direction for a new generation of the Internet and Web 3.0, it has a huge number of opportunities to promote smart cities.

The Metaverse can empower smart cities in various aspects. The Metaverse is essentially a process of virtualization, augmented reality, and digitization of the real world. The "Metaverse" is a portmanteau of "Meta" and "Verse", which originated already in the 1990s. The Metaverse is anticipated to serve as the next evolutionary phase of the Internet (Web 3.0), seamlessly blending both virtual and physical realities. Smart cities, from another aspect, strive to enhance the quality of life for citizens of smart cities, foster conducive environments for business development, and enable more efficient governance and management systems of cities. The integration of the Metaverse can empower smart cities, highlighting the pivotal technologies required for this convergence. In one key smart city scenario, the Metaverse can be seen as a viable solution for smart cities, especially the concept of a metaverse workplace, which may enable citizens to work smartly with less environmental stress of city mobility. These city planning considerations encompass ensuring privacy and security in data utilization within both Metaverse and smart city systems, bridging the digital divide to ensure equitable access to Metaverse-enabled services, establishing interoperability standards for seamless integration of various platforms and technologies, and addressing the ethical implications associated with immersive experiences. There is an imperative need for interdisciplinary collaboration to address all kinds of human-centered technical challenges. By exploring these new opportunities and challenges, scholars and practitioners can contribute to realizing a compelling and beneficial Metaverse for smart cities (see Chen et al., 2024).

In the dominating metaverse future scenario, the Metaverse depicts an immersive shared space where people walk and make contact between the real world and the Metaverse. Users can enter the Metaverse by having a computer and wearing a special pair of glasses. It is not a simple technology, but instead, a novel product that incorporates many new technologies, such as big data solutions, interactive technologies, cloud computing, fog computing, artificial intelligence apps of learning, language processing, image visualisations, 5G, blockchain, and of course, digital twins. With the advent of the Metaverse, many changes will take place. These changes can be broadly categorized into five aspects: economy, innovation, culture, life, and cities. Although it is a virtual world it makes people feel like they're in the real world. So-called metaverse workplaces will have many impacts on the operations of smart cities because any activity in the real world can be realized in the Metaverse.

Almost needless to say, these kinds of Metaverse developments have also huge impacts on data spaces, data management, and data system planning needs in city digital twins (CDTs). As a visual summary Figure 7 with (1) data conversion, data structure, and external data, (2) data collection, (3) modular DTs, and (4) Digital Twin source data and functionality sharing can be presented and delivered. These four elements are critical data planning and management elements. These data management elements need data spaces, data management, and real data planning. As underlined above, the key issues in the integration of IoT and AI are (1) security and privacy, (2) priority components, and (3) smart city awareness (see also e.g. Nguyen et al., 2024).

In general terms, inter-operationality of data facilities is a key planning challenge for smart city digital city solutions.

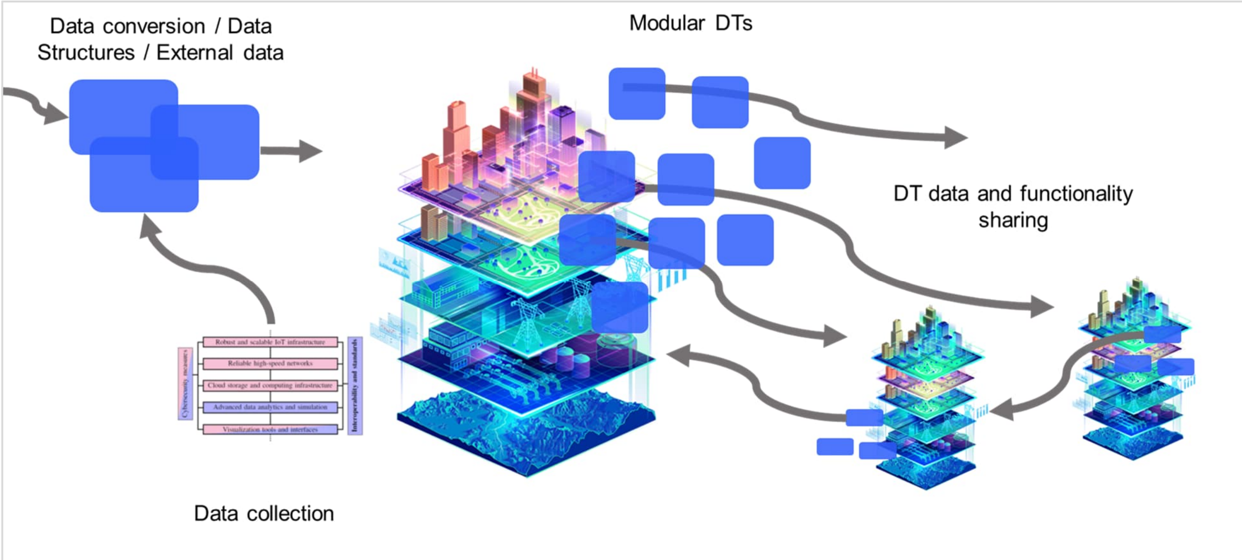

Figure 7. *Key elements of data management, (1) data conversion, data structure and external data, (2) data collection, (3) modular DTs, and (4) Digital Twin data and functionality sharing.*

Modularity and Modular Software

The emerging field of City Digital Twins has advanced in recent years with the help of digital infrastructure and technologies connected to the Internet of Things (IoT). The fast technological development requires digital twins not to be limited only to 3D models, monitoring, and visualisation; two-directional interactions between humans and computers is also required. High level of maturity of Digital Twins cannot be found in many smart city studies, high level of maturity requires advanced DT technologies and methods such as cloud computing, artificial intelligence, BIM, and GIS solutions. The DT field developments need to handle the complex urban challenges of multidisciplinary digital twins. While City Digital Twins extend by definition beyond mere 3D city modelling, some smart city studies involving 3D city models still refer to their subjects as City Digital Twins. Recent studies show that there are various needs for near-real-time data analytics algorithms, which could furnish City Digital Twins with big data insights. Other opportunities include public participation capabilities to increase social collaboration, integrating BIM and GIS technologies, and improving storage and computation infrastructure (See, Masoumi et al., 2023). It is very popular to apply maturity model thinking and platform thinking of smart city digital twins (See Aragão et al., 2023; Dani et al., 2023; Ghazinoory et al., 2023). It is important also to be aware of commercial supply of digital twins and alternative platforms of digital twins (See e.g. Dani et al., 2023; Kortelainen et al., 2022).

Larger and more complex IT systems, like city digital twin systems, have traditionally been vendor dependent. This dependency is often an obstacle for both rapid new development and when adding new logic and functionality into existing systems. Modularity in IT systems add flexibility, scalability, and ease of maintenance. Synonyms for Modularity are Composable Software, Modular Design, Component Based Software among others.

The main idea behind Modularity is that different solution vendors and developers can add, update or replace individual modules without affecting the entire application, making it easier to adapt to changing requirements and easier implementation of new technologies. Modularity also enables an easier, if not the only, way of developing and implementing e.g. an ecosystem driven Platform-Based Business.

Existing examples of successful Modularity use are:

- Django, WordPress and Ruby on Rails are examples of how various add-ons from different vendors can be plugged into the framework.
- Unity and Unreal engines enable modules for graphics, physics, and scripts.
- Platform business' like AirBnB and Bolt are built using Modularity approach.
- APIs (Application Program Interface) have been around for around 20 years and successful business models heavily rely on modular software design with APIs. This section is a snapshot of the possibilities and will focus on API based design.

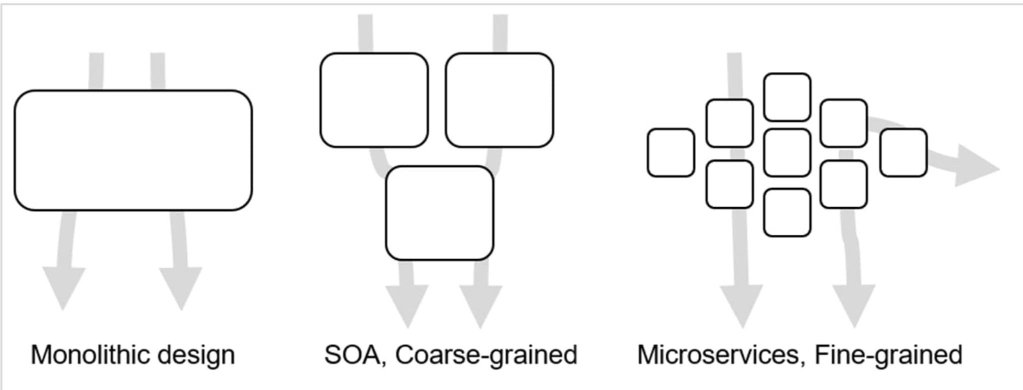

Figure 8. *Software designs and business processes.*

Monolithic design requires updates of the whole system when implementing business processes (visualized with the grey arrows). Microservices have a flexible design and only smaller modules needs to be updated when implementing business processes.

Existing Technologies for Building Modularity

There are several existing technologies for developing modular software. Some are technologies for developing software internal IT systems while some are for building interfaced systems. Below a list of some of these:

1. Object-Oriented Programming (OOP)

OOP is a fundamental concept in software development that promotes modularity. It involves designing software around reusable software objects (program parts), which encapsulate data and behaviour. Classes and objects are organized in a way that facilitates modularity and reusability e.g. objects using other objects.

2. Service-Oriented Architecture (SOA)

SOA is an architectural approach where software components are designed as services that can be loosely coupled and independently deployed. Services communicate with each other through well-defined interfaces, promoting modularity and reusability. Often implemented with Microservices.

3. Microservices

Microservices is an architectural style where an application is composed of small, independent services that communicate via APIs, it is a concept of building an application based on breaking it into multiple modules. Each module has its own specific responsibilities but communicates with others to form a unified system.

4. Modular Programming in Languages

Some programming languages provide features for creating modular software:

- Python: Python's module system allows developers to organize code into reusable and independent modules.
- Java: Java's package system helps organize classes into reusable components.
- C#: C# supports namespaces and assemblies to create modular applications.

5. Dependency Injection (DI)

Dependency Injection is a design pattern and technique used to inject dependencies (such as objects or services) into a component, making it more modular and easier to test. This could e.g. be an object handling graphics residing on a server where your software run, and you simply declare and use this object in your software.

6. Plugin Systems

Building software with plugin systems allows developers to create modular extensions that can be added or removed without modifying the core application. WordPress, as mentioned earlier, is an example of a system with a plugin architecture.

7. Package Managers

Package managers like npm (for JavaScript), pip (for Python), and NuGet (for .NET) allow developers to manage and distribute modular libraries and dependencies.

8. Component-Based Development

In component-based development, software is built using pre-made components or libraries. These components are often designed to be modular and reusable. Frameworks like React for web development and Qt for desktop applications promote this approach.

9. Middleware

Middleware components, such as message queues and application servers, can be used to create modular and scalable systems. They help handle communication and coordination between different parts of the software.

10. Aspect-Oriented Programming (AOP)

AOP is a programming paradigm that allows developers to separate cross-cutting concerns (such as logging, security, and error handling) from the core application logic, promoting modularity.

11. Containerization and Orchestration

Technologies like Docker and Kubernetes make it easier to package, deploy, and manage modular software components in containers, promoting scalability and portability.

12. Modular Frameworks

Some software development frameworks are inherently designed to be modular, making it easier to build and extend applications. Examples include the Spring Framework for Java and Angular for web development.

Modularity is a multifaceted technology and depending on the programming tool, the environment, and the goal one wants to achieve. A plugin solution is very different from an object-oriented solution, and naturally there is the option to combine different technologies. A solution with combined technologies could be described in Figure 9.

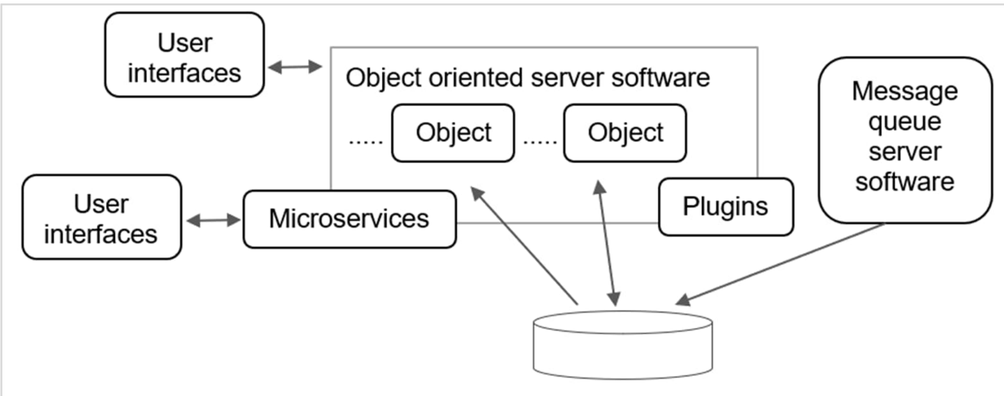

Figure 9. *Modular software design.*

Building larger scale applications with microservices and APIs

Application Program Interfaces (APIs) is a proven technology APIs are used to build business models based on static or modular software technologies and existing data sources which are domain driven. One individual API is a software product that connect computer programs with each other in the domain, and one API has one functional purpose only. This means that one API is not handling product lists as well as payments. APIs are not tech driven (technology dependent) and they do not connect to end users directly, e.g. an API has no user interface.

API based solutions require solid planning and documentation. APIs can be used internally within your organisation, with strictly with defined partners and be public used by anyone and there is no strict rule of for mixing the usage. APIs can also be a way to share and protect your data by refining the data before sharing it through an API. APIs are often used to expand and share a business model with ecosystems or vice versa (see Figure 10).

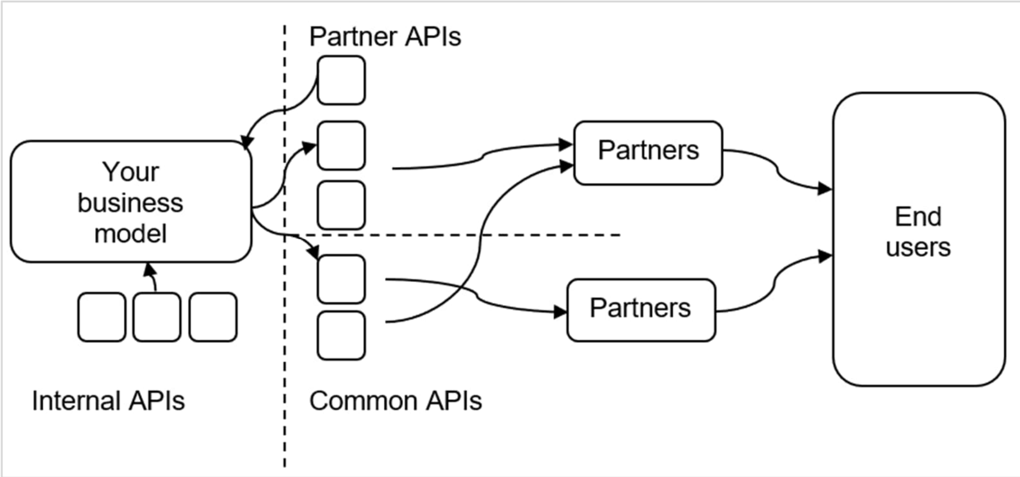

Figure 10. *APIs expanding business models.*

Partner APIs require an integration of your APIs into their user interfaces and business models. This creates a new level of control and design of your solutions. This is often referred to as your API strategy. This strategy should support your business strategy and goals and needs to be a long-term strategy with clear goals.

APIs requires partner sales, partner development and needs to be well documented. Maintenance and support should rely heavily on both end users and partner feedback. Your organisation should support and involve the stakeholders relying on your API functionality as well as your data must be solid and of high quality. The below picture visualizes some of the required organisational needs:

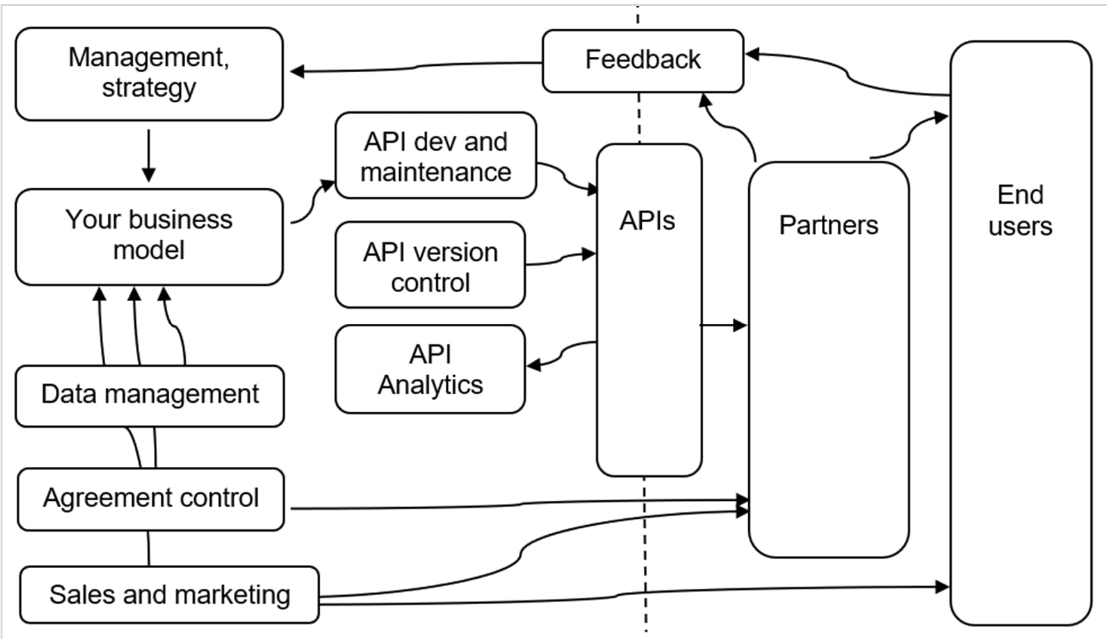

Figure 11. *APIs and organizational needs.*

It is challenging to create one complete big Smart City Digital Twin solution because a "complete" SCDT is extremely complex and will require large amounts of data from different hardware and software systems. It is therefore worthwhile, if not necessary, to break the SCDTs into smaller and reusable micro-service API components. Figure 12 portrays the idea from LIST in Luxembourg of how to split the SCDT into parts in the environmental domain.

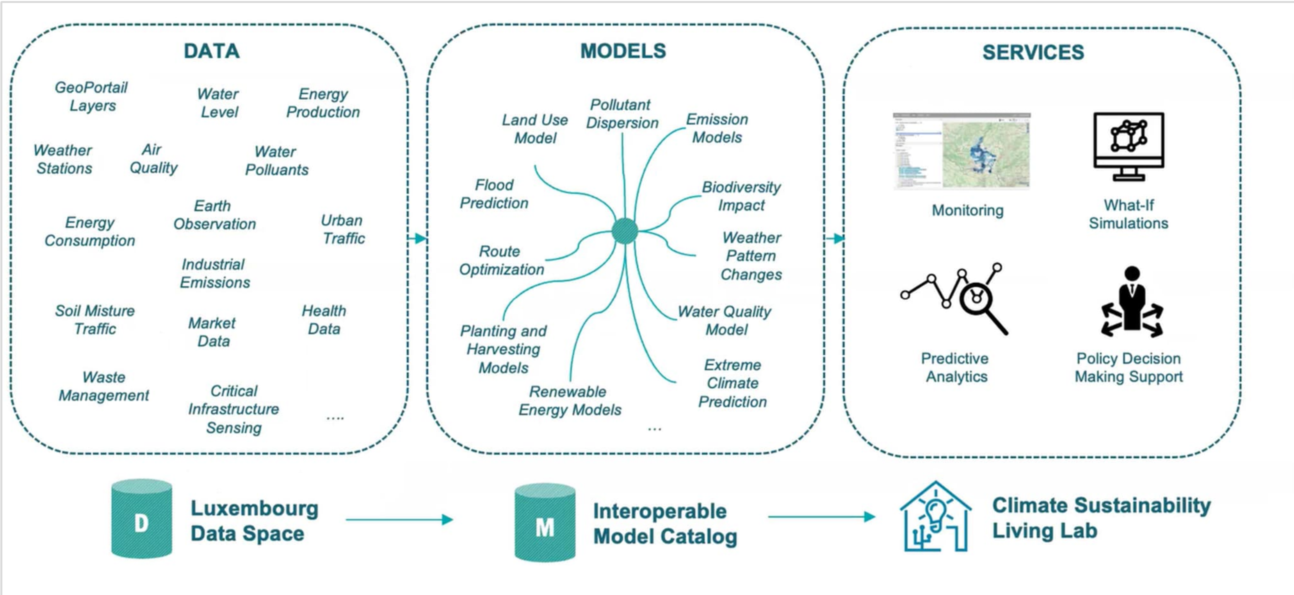

Figure 12. *SCDT in different parts of the environmental domain.*

A solid strategy and design are required for the future SCDTs where the city manages its infrastructure (components, communication, data, and business models) together with partners providing both small and large components for the functionality and the processes.

Low end standardization of hardware, communication and software are necessary for connecting components together to enable high quality data. Composable software components are required for building your internal processes supporting your business and API strategy.

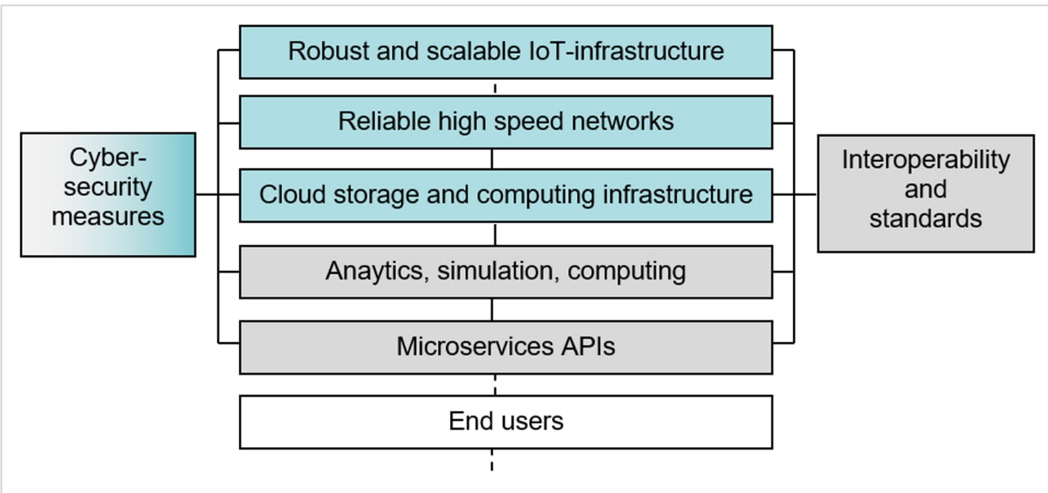

Figure 13. *Composable software components.*

Efficient SCDT development should be driven by common domain specific data structure definitions by cities. This will enable the development of mutual shareable microservice modular software products. This will lead to a rapid development and more transparent way of implementing SCDTs.

2.3. EU-Level and National Finnish Endeavour for Smart and Innovative Urban Developments

In the next sections, we discuss about EU-level and national approaches to smart urban development. First, we discuss about Smart Specialisation Strategy (S3). Secondly, we discuss about Digital Compass strategy of Finland and the European Union. Thirdly, we also discuss the European Digital Innovation Hub network strategy. These EU and national approaches are important policy strategy tools to promote smart and innovative urban development in the European Union.

Smart specialisation strategy (S3): The official strategy of the European Union

Smart Specialisation Strategy and the S3 approach is an important issue, which has various links to smart city and digital twin developments and modern city planning. According to Domique Forey (2023, p. 5) a key operation of S3 is to put in place a process of strategic interactions between the: government and stakeholders to discover (1) priorities defined as specific transformational goals within broad fields of industries, (2) the management gaps, problems and opportunities which characterize such transformations, and eventually (3) the policy initiatives to be taken in response. The outcome of this S3 management process is a transformational roadmap which forms the basis for designing and implementing policy programs (such as call for proposals, procurement, prizes, the provision of new infrastructures, etc.).

Thus. it is very important to coordinate S3 approach with smart city initiatives and strategies. In many city planning cases, policy coordination is not happening in European cities, and many national and regional strategies are not integrated, which is a problematic issue for the impact of EU policies, but also a serious problem for the impact of national and regional policies. S3 practices have evolved since 2012 as lessons from the first period of implementation were drawn. However, the main principles of selecting and establishing city planning priorities remain still intact. The S3 policy framework will support concentration and density, because innovative activities have always scale and agglomeration economies to be impactful.

For example, national and regional S3 programs need to target SMEs, and start-ups, to attract large companies, and to support partnerships and networks. This key function of S3 framework approach and S3 strategy planning work needs to be linked to smart city and digital twin development activities. because scale and agglomeration economies need to be realised in practice.

Four key elements of S3 approach

Key four elements of S3 framework are the following ones (see Foray, 2023, p. 6–7). First, there is a need to encourage regions to *identify priorities* and thereby *build new competitive advantages* based on their specific spatial strengths, potentials, and opportunities, rather than doing just (imitate) what the others do. This is a fundamental reason why it is not always wise to follow existing trends and conventional approaches. The initial S3 framework idea was based on the observation of many cases of policy decisions, which were taken with no relation to regional assets of endogenous growth (human capital, demographic population structures, and knowledge assets), but just followed some trendy topics. This vague strategic approach is not a very smart strategic choice if it neglects driving forces of endogenous growth. Regions need to particularize themselves by selecting priorities, based on regions' specific knowledge and human capital capacities and opportunities linked to demographic structures.

Second, *priorities are vertical – target specific industries/firms* – a logic of intervention which is opposed to horizontal interventions which concentrate on a few aggregate capacities and categories such as SMEs, corporate R&D investments, the spirit of entrepreneurship, universities, or business environment. Vertical logic concentrates always on a particular industry or group of industries. While *horizontal policies* are always important to design and implement, vertical interventions are also key for two logical reasons: Some industries are more promising in Region X compared to Region Y in terms of capacities, potentials, and opportunities (Zachman & Bergamini, 2020). As already said, *support systems for innovation need to be specific, not general*. For example, if we want to support the development of digital twins in a city, we must have specific support systems, not only very general. But, by definition, a horizontal policy cannot capture such specific nature of public inputs, services, infrastructures, or coordination problems. Vertical policies that target specific industries can address the specific needs, gaps, and opportunities of the concerned industries (see Foray, 2023, pp. 6).

In addition to regional horizontal strategy issues, attention should be paid to vertical integration measures. Often, sensible integration measures can promote regional competitiveness, resilience, and the innovation ecosystem of city region X. This kind of vertical integration principle is key for S3 to depart from the old style of industrial policy which targeted preferential interventions but at the same time gave rise to *the usual problems of picking winners and supporting losers*. The idea of S3 is to *pick change makers*. Hence, each priority area includes one or several sectors as well as a transformational goal. If both elements are combined, they build *a specific priority area, a cornerstone of a regional smart specialisation strategy.* This aspect of *priority area selection* means important implications for smart city and digital twin developments (Foray, 2023, pp. 6). Comparative advantages need special attention in modern city planning. Comparative advantage is an economic theory that describes a development scenario where a country or city entity can produce a specific good or service at a lower opportunity cost than another country or entity.

Fourth, *priorities need, in any case, to be specific* – to send clear signals to key change makers and agents, enhance coordination, and support density and agglomeration around a specific objective of transformation. The future does not happen; it is always made by some ones. For change to happen, someone has to see the problem, develop a solution and get others involved, also in cities and urban environments. Within the framework of an S3 priority, the policy will support innovative activities along three dimensions: (1) Providing specific public inputs, (2) supporting concentration of critical resources and networks of actors (innovation networks) and (3) solving coordination problems, there are many public goods which are industry-specific such as specialized skills and core competences, new knowledge, technologies, services, and infrastructures. A public good is a commodity or service that every member of a society can use, without reducing its availability to all others. Typically, a public good is provided by a government and funded through taxes. The provision of public good challenge means that there is not part of the generic policy agenda but on the other they can't be provided (or are underprovided) by private agents and change makers. Vertical interventions will support the provision of these industry-specific public goods (Foray, 2023, p. 7).

The S3 policy will support concentration, density because innovative activities have always scale and agglomeration economies. One of the major subfields of urban economics, economies of agglomeration (or agglomeration effects), explains, in broad terms, how urban agglomeration occurs in locations where cost savings can naturally arise. This term is most often discussed in terms of economic firm productivity. For example, S3 programs need to target SMEs, attract large companies, support partnerships and networks, and create in this way new agglomeration economies. Many transformations at the industry level raise issues of complementarity. A perfect complement is a good that must be consumed with another good. Few goods behave as perfect complements. One classical example is a left shoe and a right; shoes are naturally sold in pairs, and the ratio between sales of left and right shoes will never shift noticeably from 1:1 relationship. The degree of complementarity, however, does not have to be mutual; it can be measured by the cross-price elasticity of demand. In the case of video games, a specific video game (the complement good) has to be consumed with a video game console (the base good). However, it does not work the other way: a video game console does not have to be consumed with that game. The complementarity of digital twins may need special attention also in urban planning. In some cases, digital twins can be like two shoes (left and right shoe). If you have one "left shoe digital twin", you need to have "right shoe digital twin", just to present a good example. The point is that many companies (start-ups, large firms, SMEs) are willing to contribute to the development of this digital twin industry and can propose new and innovative business models. However, these business models can make sense only when other, complementary models are already in place. If there are no complementary business models available, there will be serious problems ("a missing right shoe digital twin problem"). If all technologies and systems were realized together in a region, they would form a self-sustaining system with potentially important profits. This is a very good advantage for a successful regional economy. But, there are a lot of obstacles dealing with asymmetries of information and the challenges of capturing surplus from such complementarities – where the success of a given project depends on the success of another. *It is therefore important to identify and support systems of complementarities* (see Foray, 2023, p. 7).

This aspect of complementarities is highly relevant also for the development work of digital twins in smart cities. A key element of S3 framework approach is the *Entrepreneurial Discovery Process* (EDP), which can always support smart city and digital twin strategies and implementation of them. According to scientific discussions, the EDP approach is a bottom-up process involving stakeholders to elicit critical information about the specific gaps, needs, and new opportunities within a given priority area and identify the relevant policy actions. This bottom-up discovery process will uncover a collection of complementary activities – covering a multitude of dimensions, also relevant for digital twin developments. This smart roadmap could under no circumstances have been imagined or predicted by the government alone. This is why the collection of complementary digital twins can make a sense (see the discussion of Foray, 2023, p. 8).

Updated information about the specific gaps (of digital twins) is very important for the development work of digital twins in smart cities. Reinventing a wheel is not a signal of ultimate smartness.

S3 and regional choice of policy instruments

Driving transformations towards certain strategic goals or city vision in regional policies may require the deployment of several policy instruments and provide new opportunities for running policy experiments and designing novel policy initiatives like developing smart city digital twin policy. It also requires flexibility and constant adjustment of the urban policy instruments to meet the uncertainty of project's implementation and performance. This city planning challenge is relevant for city policy. The bigger the city or metropolitan region is, the bigger is this regional planning challenge (Foray, 2023, p. 8).

It is important to highlight here the multi-dimensional nature of any regionally relevant vertical transformation. For example, the development of a circular economy in the food industry or the generation of digital transformation in the healthcare industry. These urban planning issues are very relevant issues for smart city planning, too. A vertical transformation has multiple determinants and policy levers. This is why the problems to be solved and the opportunities to be realized are many and proceed from different policy areas: human capital, R&D and innovation, knowledge assets, infrastructure and services, technology diffusion, cluster, and networks (see Foray, 2023, p. 8–9).

Thus, the smartest solutions cannot be planned without understanding vertical transformation in city regions. In the same vein, innovation as a key engine of any S3 framework needs to be understood in a broad sense- This planning challenge means that, for many regions, S3 framework approach will not be deployed to invent at the frontier but rather to generate "innovational complementarities" in existing industrial and service sectors (See, Trajtenberg, 2010), which involve innovation-related activities such as (1) technology adoption, (2) training, (3) knowledge management, (4) skills development (including digital twins and smart city planning concepts), (5) the creation of new organizational structures and/or (6) business models in companies, (7) the implementation of novel management practices or (8) the provision of specialized business services and (9) infrastructures for product and process development. This can also mean that city planners need to have *special planning infrastructures for digital twins*. Then, as policy actions need to be formulated to address all the issues (solving problems, filling gaps, and realizing opportunities), the so-called Tinbergen assignment theorem applies. The Tinbergen assignment problem concerns the allocation of policy instruments to policy targets to improve policy effectiveness. Policy instruments are the variables or procedures that policy authorities directly control. Policymakers' use of these instruments to achieve objectives (i.e., policy targets) directly affects the welfare of their constituents. (Tinbergen, 1967).

Following Tinbergen rule (1967) there are several policy goals and often an array of specific concerns, one will need to have as many separate policy instruments as there are targets. This may mean that we really must define the number of digital twins in a certain smart city setting, which is taken seriously in the city planning and policy process. In another case, we may make many urban planning mistakes. This is why the Entrepreneurial Discovery Process (EDP) is not only crucial to identifying these specific problems and opportunities but is also instrumental to exploring the rich toolbox of innovation policy to propose a relevant instrument for every issue that needs to be addressed. challenge (See, Foray, 2023, p. 8–9).

In many regional planning cases, while the EDP was effective in identifying specific problems, gaps, and opportunities, the suggested policy responses were poorly formulated and the EDP participants overlooked the diversity of the policy tools which are available and were not able to respond to new problems and opportunities arising during the roadmap development. The limited scope and poor urban and regional policy design of the potential instruments are reported by Gianelle et al. (2017 and 2019) and Prognos and CSIL (2023). For instance, Prognos & CSIL observe the dominance of one policy instrument – which is the call for proposal – and argue that this policy instrument is in most cases poorly designed. Indeed, they show that the majority of the S3-related calls for proposals address all priority areas at the same time. This is not good for the smart implementation of regional smart specialisation strategies. Clearly, by addressing all priorities at the same time, calls do not consider sectoral and technological specificities, as the very fundamental logic of smart specialisation would advocate (See Gianelle et al., 2019).This aspect of S3 policy field policy needs reconsiderations.

Policy tool package of the European S3 approach

In the European Union, S3 policy framework instruments are designed and deployed to support innovation through different logic (Foray, 2023, p. 11). Under so-called ***a push logic***, the instrument addresses essentially the cost of innovation activities. This kind of push logic includes the direct provision of research through government labs, directed grants and subsidies to R&D, R&D tax credits, subsidies to transfer of technologies or to support innovation adoption.

Under the framework of ***a pull logic***, the instrument addresses essentially the reward for a successful innovation activity. The most important pull policy is patent protection but, in many sectors, and circumstances ex-ante prizes and advanced market commitments are gaining in importance of policy making. ***Public procurement for innovation*** can also be considered a pull instrument of regional innovation policy. Under ***a coordination logic***, the instrument addresses potential coordination failures, which arise from the strategic complementarities among actions or investments. Coordination failures arise often from a hidden hypothesis of self-fulfilling prophecies. Things are expected to happen automatically like self-fulfilling prophetics. *Strategic complementarities* mean that supporting one action or investment will increase the return to support another. Under such principle, policy instruments are designed to capture such complementarities (e.g., support different types of investments simultaneously), but this kind of management process is not happening automatically.

Under ***an institutional design logic***, the instrument proposes a new organizational design for complex innovation management problems – which cannot be addressed by the more conventional policy instruments. This is typically the case for the development of partnerships between SMEs and Universities or Quadruple Helix partners or the support of entrepreneurship through multiple actions. The final logic includes instruments, which are usually used for policy interventions in other policy areas such as ***human capital supply*** (primary, secondary, tertiary education, and adult education).

The S3 framework approach implies that the development of integrated smart city digital twin approach must have a clear strategy of push and pull logic as well as coordination and institutional logic with human capital supply.

Previous regional and urban studies have presented the newly developed "***S3 Platform***," (https://s3platform.jrc.ec.europa.eu/) which can be used to compare and evaluate smart specialisation strategies in the European Union. The S3 Platform assists EU countries and regions to develop, implement, and review their Research and Innovation Strategies for Smart Specialisation (RIS3). This RIS3 Platform and Scoreboard tool has now been developed further to include the comparative assessment of all smart specialisation strategies and the creation of a comparative map for all regions. It is good to know this tool and we can potentially apply it also in smart city digital twin projects. The S3 Scoreboard covers about 163 regions in 28 EU countries. In addition, S3 strategies at the country level, such as in Malta, Luxembourg, or Cyprus, are included.

The scoreboard provides a detailed breakdown.

1. of performance groups/stakeholders with contextual data, including the share of the ERDF budget associated with S3 priority areas,
2. the continuity analysis of the so-called Entrepreneurial Discovery Process (EDP), or
3. the project selection criteria for S3-related calls for proposals under the ERDF 2014–2020.

T*ransforming Territories Newsletter – Smart Specialisation Platform* (see https://s3platform.jrc.ec.europa.eu/transforming-territories-newsletter) is a very good way to follow recent development of European RIS3 issues and gain regional integration advantages.

Based on these pieces of information the maturity of S3 framework strategies across the EU can be analysed and compared now and in the future with this European S3 planning tool. Overall, the S3 scoreboard information shows a strong variation that reflects the different starting points for smart specialisation strategies in terms of the strength of the research and national and regional innovation systems, the level of available resources compared to the national resources, and the level of aid intensity. Many S3 leaders are found in less developed regions, while the Nordic countries, the United Kingdom, or some German, French, and more developed Spanish regions show potential for optimisation in their national S3 strategies.

The 22 national S3 strategies in the EU perform relatively well, but there are still many strategic fields of improvement. One of them is surely the smart city field of regional development.

The Vision of Digital Compass in Finland

The digital compass vision in Finland till 2030 sets national targets for the effective use of digital systems so that Finland can succeed in the ongoing digital transformation in the European Union. This Digital Compass vision is, of course, very relevant for smart city digital twin strategies of the Finnish cities. The Digital Compass vision strengthens the shared understanding of the benefits, concepts and direction of digitalisation and the data economy. Finland's digital compass is actually based on the EU's Digital Compass, introduced in 2021, and the related programme proposal 'Path to the Digital Decade,' (European Commission, 2021) which defines the requirements for national DC roadmaps.

The Description sheet of Digital Compass report of Finland (Finnish Government, 2022, description sheet) defines the vision in the following way:

"The Digital Compass shows the way as we create a common roadmap for the development of digitalisation and the data economy. According to the vision, we are building a digitally capable Finland that is attractive, competitive, sustainable, and prosperous. We will achieve this through competitive and innovative business activities, high-quality expertise, broad-based education, people-oriented public services, and safe and high-quality infrastructure. Achieving the objectives set for the Digital Compass calls for extensive systemic change; determined cooperation with the public and private sectors, universities, research institutes and organisations. To accelerate digitalisation and the data economy, we need investments and cross-sectoral practices."

The meaning of this vision for smart city digital twins is that investments are needed and there is an urgent need for cross-sectoral data management practices. Central policy instruments are extensive systemic change, determined cooperation with the public and private sectors, universities, research institutes, and civil society organisations. This approach underlines the importance of Quadruple Helix collaborations.

Finland aims to be the first EU Member State to draw up a national strategic DC roadmap. The measures to be taken to put Finland's digital compass into action, and the investments they require, will be defined for each government term, and updated annually between now and 2030. Decisions on national funding will be made as part of budgetary processes, and opportunities for the use of EU funding will also be explored. The coordination group for digitalisation will be responsible for monitoring these measures and coordinating work between stakeholders (Valtioneuvosto, 2021). *This yearly monitoring mechanism of Digital Compass if Finland need to be connected to smart city digital twin activities of the Finnish cities.*

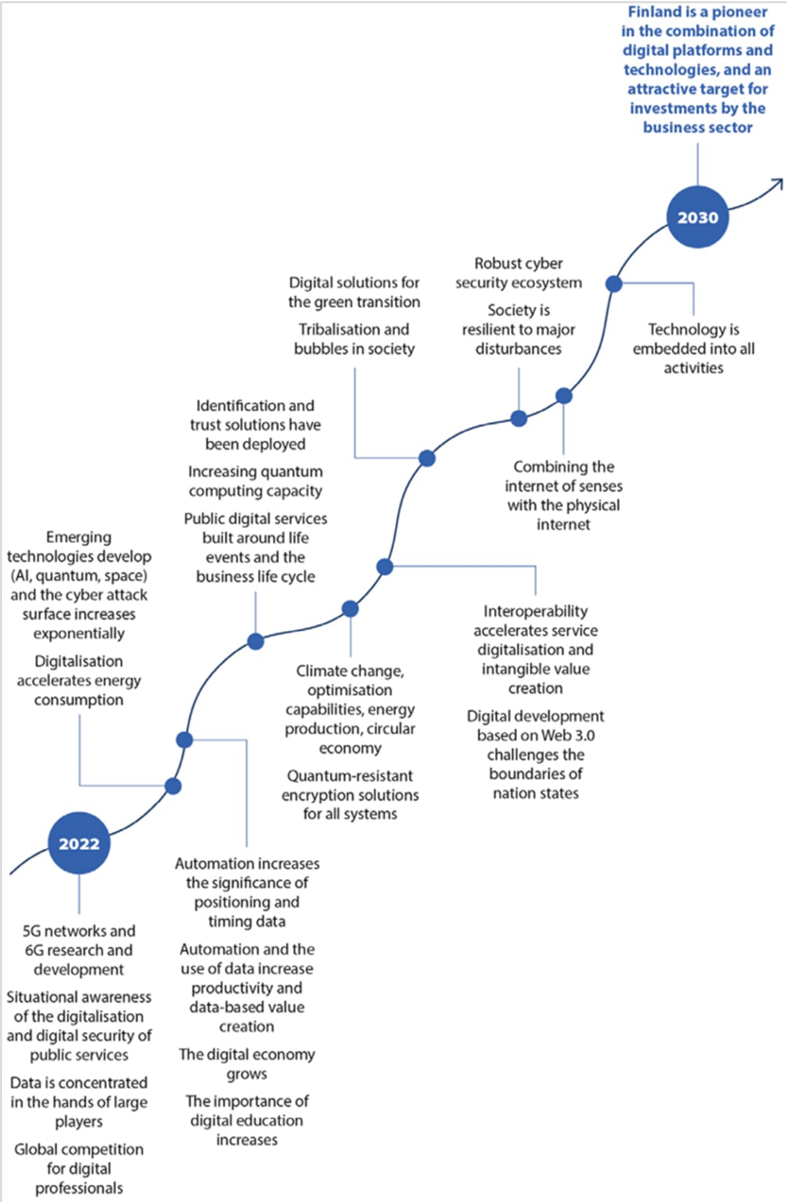

Figure 14. *Roadmap of Digital Compass of Finland. Global and national phenomena affect Finland's opportunities to successfully take advantage of digitalization and create solutions for the digital economy. (Government of Finland 2022, 11).*

Figure 14 tells us clearly that all essential elements of smart city digital twins are in the roadmap of Finnish Digital Compass and vision.

The societal transformation caused by digitalisation and the data economy is changing Finland and also the whole world. A data economy can be seen to be a global digital ecosystem in which data is gathered, organized, and exchanged by a network of companies, individuals, and institutions to create economic value. It will be reflected in new kinds of services in cities, operating models (like smart city digital twins), technologies and skills requirements in every sector of society. Also, the digital green transition with Sustainable Development Goals (SDGs) requires a comprehensive societal change, which also involves major opportunities for Finland and city regions. However, according to the Finnish Government, Finland´s current challenges include (1) a low amount of ICT investment aimed at increasing productivity, (2) a shortage of skilled ICT professionals, (3) societal marginalisation (with increased digital divide problems), (4) the changes in operating culture and (5) new emerging paradigms required by digitalisation. These listed challenges require much attention in city planning and among professionals and stakeholders of city planning (see Finnish Government, 2022; Valtioneuvosto, 2021).

Figure 15 summarises key variables of Finland´s digital future and digital compass (Finnish Government, 2022). The digital compass and the cooperation that will emerge around it are important tools for building Finland's future paths of digitalisation. The digital compass of Finland is, first and foremost, a tool for the central government to steer the development actions of digitalisation, but also the setting and achievement of national objectives will require the participation of society as a whole, including the city regions and regions of Finland. As we see, the Government sees *skills, infrastructure, public services, and business* to be the key four strategic elements of the digital compass of Finland. All these elements are linked to smart city digital twins (SCDTs), which is, of course, a strategic focus of national and regional digital twin collaboration.

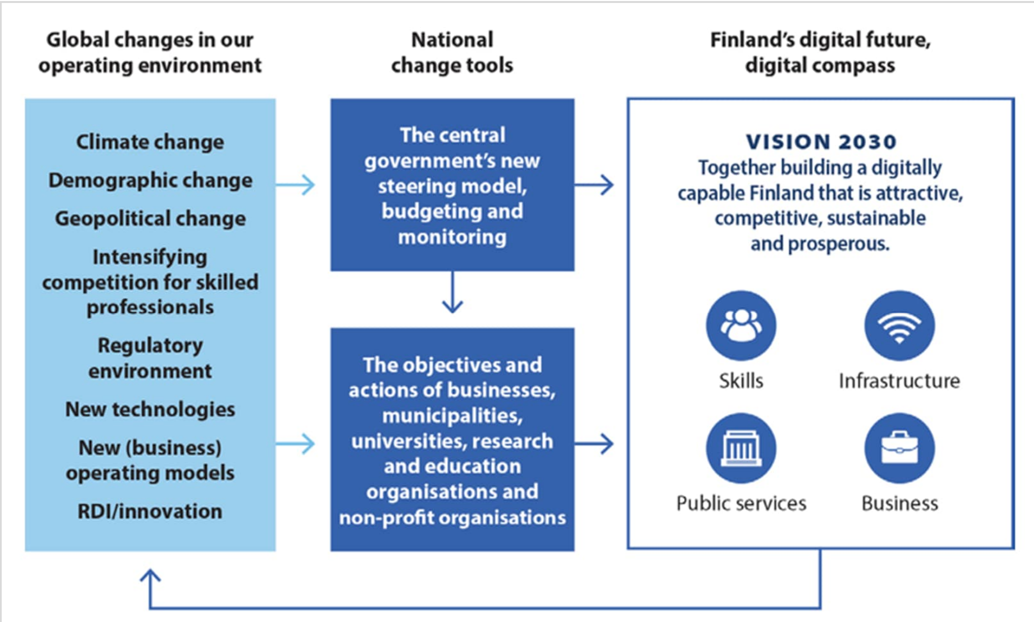

Figure 15. *Monitoring and Finland´s digital future, and digital compass (Government 2022, 27).*

It is good to keep this figure 15 in mind when future developments of smart city digital twins are monitored yearly, if we want to behave strategically in the future.

European Digital Innovation Hubs Networks

The European Digital Innovation Hubs (EDIHs) networks are an important strategic EU approach for the European Union to promote digitalization and smart city development in the European Union. Today the European Digital Hubs (EDIH) Network is a strong driving force behind Europe's digitalisation among companies. With the support of the European Commission, this network strategy brings together all country-level EDIHs, small and medium-sized enterprises (SMEs), and public sector organisations (PSOs) to make the EU's Digital Decade 2030 targets a reality. We can see the link of European digital compass strategy to the EDIH networks. The

EDIH Network comprises of all 228 EDIHs in Europe. Of these EDIHs, 151 EDIHs receive funding from the European Commission's Digital Europe Programme, while 77 EDIHs are funded by national or regional resources. The EDIH network's core strategic mission is to build up the digital capacities of companies and public sector organisations. The future mission of EDIH network strategy is the following (European Digital Innovation Hubs, 2024, see https://european-digital-innovation-hubs.ec.europa.eu/home):

- Advance digital transformation across the EU by bringing cutting-edge tech (AI, Cloud Computing, Big Data, Internet of Things, Machine learning, etc.) to 75% of European companies.
- Ensure that over 90% of companies have a basic level of digital know-how in their business organisation and operations.
- The strategic target is to create new value chains within the European Union.

To accelerate digital transformation in the European Union, the EDIH Network leverages nrw cutting-edge digital technologies (Industry 4.0 techs) in key sectors across all EU Member States as well as Iceland, Lichtenstein, and Norway (see more https://european-digital-innovation-hubs.ec.europa.eu/home). The European EDIH strategy is directly and indirectly linked to smart city development activities through companies and other innovation actors of business ecosystems. Therefore, the country-level and European EDIH networks should be consciously utilized in smart city development activities. The four European EDIHs selected from Finland are:

1. EDIH Robocoast, with Prizztech Oy as coordinator (manufacturing industry, Web: https://robocoast.eu/),
2. EDIH HealthHub Finland, with Turku Science Park Oy as coordinator (health), Web: https://healthhubfinland.eu/
3. EDIH Finnish AI Region, FAIR with the City of Helsinki as coordinator (digital services, smart cities and health), Web: https://www.fairedih.fi/
4. EDIH Location Innovation Hub, with National Land Survey of Finland as coordinator (geographic information), Web: https://locationinnovationhub.eu/fi/

3. INTEGRATING SMART CITY AND FORESIGHT APPROACHES

Typically, foresight research employs a variety of methods, such as trend analysis, scenario building, expert panel discussions, surveys, and simulations. The objective is to generate information that assists organizations and decision-makers in making strategic decisions and planning for the future. It is always important to note that foresight research does not attempt to predict the future with high precision. Instead, it identifies various possible futures and helps in preparing for uncertainty and risks. The insights gained from foresight research can aid organizations in adapting to changes, seizing opportunities, and minimizing too big risks. Overall, foresight research is a forward-looking and strategic approach to understanding and navigating the complexities of future developments.

This Smart City Digital Twin study was mixed quantitative-qualitative research with practical and developmental orientation, originating in the interdisciplinary field of future and foresight studies. The selection of foresight methods has been dominated by the intuition, insight, impulsiveness, and sometimes – inexperience or irresponsibility of practitioners and organisers. In this study, we have wanted to avoid this kind of approach and select a reliable set of foresight methods. Our methodological approach in the Smart City Digital Twin project has been that the selection of foresight methods is a multi-factor process and needs to be considered as such. We have wanted to cover key dimensions of methodological dimensions.

The methodological framework of the Smart City Digital Twin project is figured out in the Futures diamond model (Popper, 2008) above. We have also taken into consideration Voros´s suggestions for foresight methodologies, (1) aiming to create relevant "forward views" and/or (2) "images of the future" ("prospective" methods) (See, Voros, 2006). We have placed key methods of the SCDT project in this well-known framework, where key methods are classified to be creativity methods, expertise methods, interaction methods, and evidence-based methods. The Future Diamond framework helps us assess the coverage of foresight methods in connection with foresight projects. It is important to choose methods that are relevant from the perspective of research problems. Methodological heterogeneity is also important, which helps to achieve a diverse overall picture of an anticipated subject matter. The creativity dimension was covered by the Smart City Wheel methodology. The expertise dimension was covered by the Smart City Digital Twin review article. The interaction dimension was covered by Smart City Digital Twin workshops in four cities (Gdańsk, Wrocław, Vilnius, and Turku). The evidence dimension was covered by Smart City Digital Twin survey research in four cities.

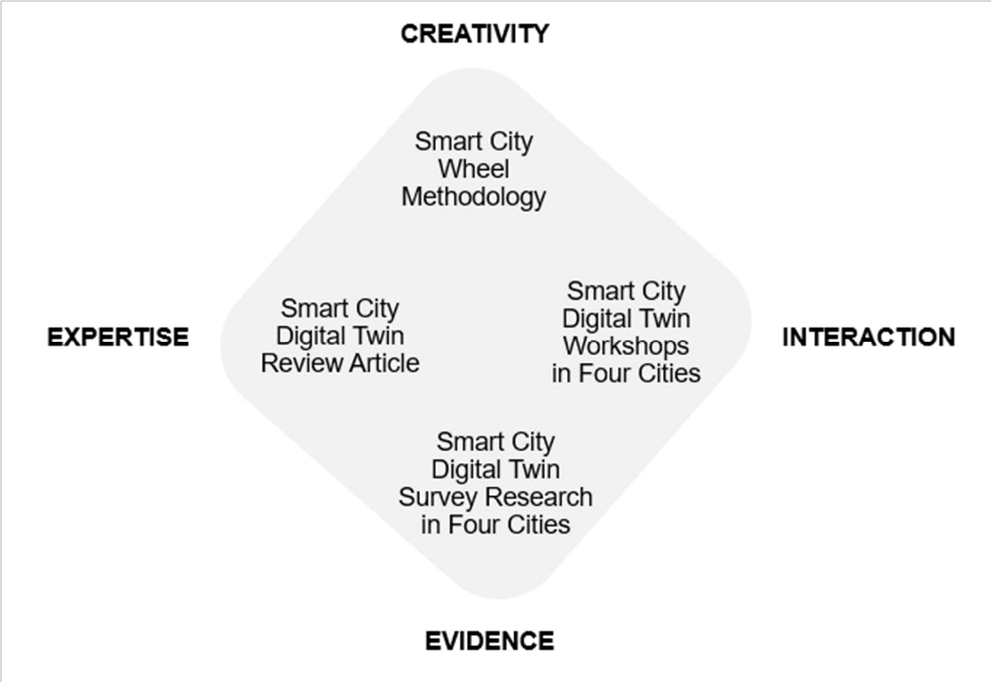

Figure 16. *Futures diamond model applied in the Smart City Digital Twin project.*

It is observed in Figure 16 that selected key methodological dimensions have covered all four fundamental dimensions of Popper's futures diamond model.

The study explores the most important Digital Twin solutions and needs related to urban environment and the benefits that can be obtained from them. These are divided into three groups:

1. Current solutions

There are four cities that operate in three countries. The workshops will find out how cities work at the moment. By sharing the current situation of different cities, we find out:

- current systems (short written descriptions and assessment of benefits),
- current suppliers and their abilities (short written descriptions),
- what kind of data repositories currently exist (assessment of transparency and scope), and environmental impact assessments (verbal estimates of effects).

2. The needs of the near future

The analysis of near-future needs helps to understand what kind of fast-coming needs exist in different cities. This helps to target the development and possibly find common needs that can be met quickly:

- Systems to be developed (short written descriptions, estimates of benefits as well as timetables and costs)
- Challenges (short written descriptions and an estimate of how the challenges can be solved)

- Interfaces, modularity, and data (estimates, how these can be utilized)
- Assessments of environmental effects (verbal descriptions and assessments of the effects)

3. Visions

What kind of SCDT services can we expect in the future. Future opportunities and challenges are envisioned:

- Different SCDT visions are described (verbal descriptions and estimates of effects)
- What kind of research and education is needed to implement the visions (verbal descriptions and estimates of effects)
- How standards, open source codes, modularity and data repositories can have an impact (verbal descriptions and assessments of effects)
- Assessments of environmental effects (verbal descriptions and assessments of effects)

In addition, the study aims to investigate the actors and stakeholders in the participating cities, their abilities to deliver SCDT solutions, existing SCDT data sources and source data for various SCDT-related studies.

3.1. Boyd Cohen’s Smart City Wheel

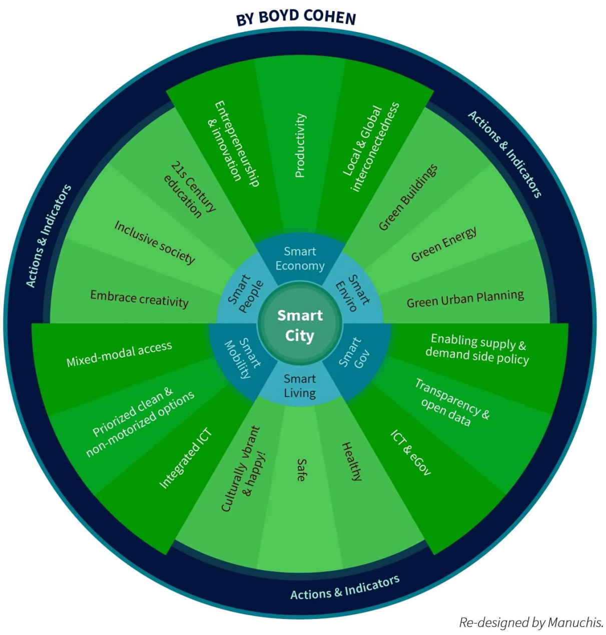

Figure 17. *Cohen’s Smart City Wheel. Source: Cohen, 2014.*

Boyd Cohen’s Smart City Wheel – (SCW) is a framework and benchmarking tool for understanding six key components of a smart city: Smart Economy, Smarty Government, Smart People, Smart Living, Smart Mobility and Smart Mobility. The rankings were done by combining publicly available data (i.e. secondary data) with data collected directly from eligible cities (primary data) around the globe.

SCW v.01 have been conducted by collecting data on 28 indicators across the Smart Cities Wheel until 2014. Yet, in collaboration with the advisory committee, in 2014, indicator numbers raised to 62. 16 of them are also directly mapped to the ISO standard (ISO 37120:2014) introduced in 2014 (Cohen, 2014).

Cohen (2014) provides a comprehensive explanation of the SCW, detailing that each of the six components encompasses three subcomponents, resulting in a total of 18 subcomponents. Additionally, there are 62 Key Performance Indicators (KPIs) used for benchmarking and assessment, as outlined in Appendix 2 (Smart City Index Master Indicators Survey, Smart Cities Council). Each of the six components is given a maximum of 15 points, with the results standardized such that the highest-performing city in each category receives the maximum score of 90 (Qonita & Giyarsih, 2023).

Boyd Cohen’s SCW is used for assessing and benchmarking performance of a city's growth and performance in six-dimensional wheel framework. Each dimension and sub-dimension are supported by key performance indicators (KPIs) that assess specific indicator of that dimension. For example, Smart Environment includes metrics for sustainability certification, smart meter uptake, and building automation technologies. (e.g., the percentage of commercial and industrial buildings equipped with smart meters reflects the city's degree of energy monitoring and efficiency. Similarly, the number of LEED or BREAM-certified buildings demonstrates a dedication to environmentally friendly construction standards).

Some KPIs consider energy use, carbon footprint, air quality, waste, and water consumption. For example, the proportion of total energy generated from renewable sources demonstrates the city's commitment to lowering its carbon impact. Similarly, such indicators relate to resilience. For instance, climate resilience planning, population density, and access to green areas. The presence of a public climate resilience strategy implies readiness to face climate-related concerns. Population-weighted density and green space per capita indicators demonstrate urban planning attempts to promote sustainable and habitable environment.

After introducing SCW and following updates by Boyd Cohen with new developments such as integrating 16 KPIs of ISO 37120 standards, scholars become utilizing it not just a benchmarking tool for comparing the performance of cities, but a versatile tool for variety of purposes. For example, Benamrou et al. (2016) compared the SCW to the Giffinger et al., (2007)'s ranking European medium-sized cities and EU-level Mapping Smart Cities in EU (Directorate-General for Internal Policies of the Union - European Parliament, 2014) frameworks and developed a new, more local assessment model. Also, scholars like Qonita & Giyarsih (2023) and Saqip et al. (2022) have used it for their regional smart city benchmarking. The most innovative application of SCW was made by Shtebunaev et al. (2023) in "Planning the Smart City with Young People: Teenagers' Perceptions, Values and Visions of Smartness". According to their experience, the SCW offered helpful framework for concentrating young people's as future citizens' knowledge of the opportunities and areas of the city where technical advancements are considered. It also made the definition of the smart city concept more visually appealing by six smart city dimension and feasible to assess elements of each city (Shtebunaev et al., 2023, p. 62).

3.2. Data Collection & Analysis

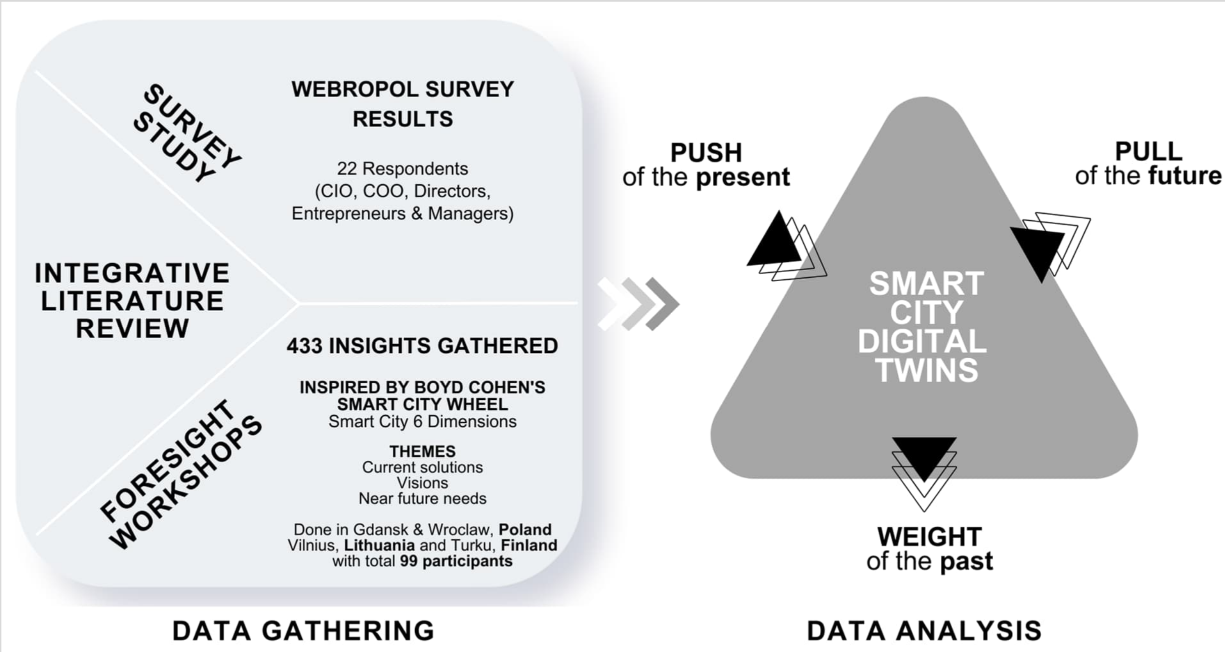

Figure 18. *Research design.*

As a first phase of examining the case cities, a Webropol-based survey was conducted. The purpose of the survey was to map out the current state of smart city and digital twin development in the four cities of Turku, Gdańsk, Wrocław and Vilnius. The survey (see Appendix 1) was outlined based on the research setting of the project. Questions were divided into four categories: 1) background information, 2) context mapping, 3) current solutions and technologies, 4) foresight and future plans. The survey was held open for 1 July to 15 October 2023 and total of 22 responses were received. The survey was targeted to all the four case cities and local partners were asked to distribute the link to relevant networks. The link was also shared via social media in LinkedIn.

The survey consisted of open-ended questions and the data that it provided was qualitative in nature. The survey was designed as an expert survey treating the information the respondents provide as facts. Majority of the data was technical in nature: questions about the existing solutions, systems, databases, service providers etc. This data was mainly categorized and grouped. The more open questions concerning motivations, challenges and expectations regarding SCDT development were thematically analysed utilizing the futures triangle framework (see Chapter 4.8. Futures Triangle Analysis: The Past, Present and the Future of SCDTs).

The information provided by the survey was used as background knowledge for designing the case city workshops. Total of five workshops were organised for data gathering purposes. The workshop in Gdańsk was organised on 19 September 2023 in Wrocław on 21 September 2023 and in Vilnius on 5 October 2023. In Turku two workshops were organised, first one on 2 November 2023 and second one on 22 November 2024.

The workshops were designed to provide information on current solutions, near-future needs and future visions regarding SCDT development in each city. The workshops were designed around the Smart City Wheel model developed by Boyd Cohen, as it provided a comprehensive framework for various aspects of urban development onto its six dimensions: smart mobility, smart living, smart economy, smart government, smart people, and smart environment (Figure 19 & Figure 20). Its use of standards, such as the 16 KPIs of ISO 37120:2014 assured insight consistency and comparability, allowing for meaningful city-level comparisons. The six dimensions were useful in addressing current challenges, future needs and long-term visions related to cities' urban development and SCDT patterns and gathering actionable insights in a limited time of a half-day workshop.

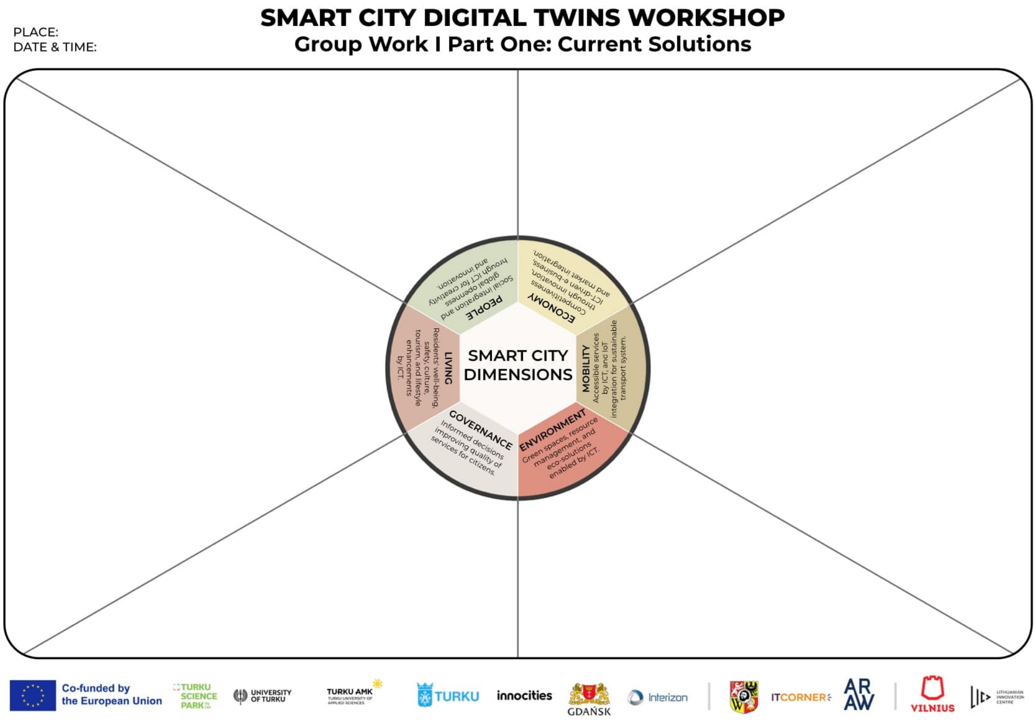

Figure 19. *Workshop sheet addressing current solutions.*

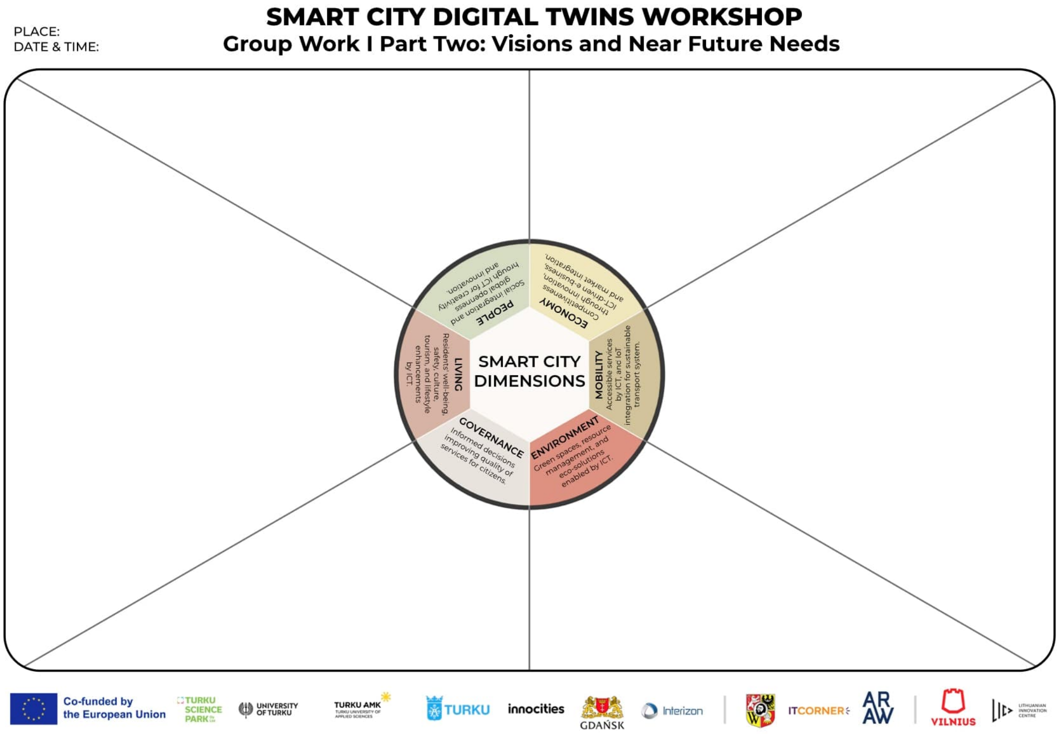

Figure 20. *Workshop sheet addressing visions and near future needs.*

The workshops provided a multifaceted view of urban challenges by including a wide range of stakeholders, including city officials, businesses, individuals, students, and SC and DT experts. Participants discovered advantages, interrelations of their visions within six dimensions, deficiencies of current solutions, and plausible future paths for SCDT developments.

The qualitative data provided by the five workshops was analysed with content analysis utilizing the smart city wheel framework as the lens. The data was first analysed individually for each city and then merged into collective analysis. The analysis of each temporary dimension (current, near-future and far-future) was done separately.

3.3. Benchmarking Smart Cities: Towards Benchmarking, Benchlearning and Benchaction Processes

This smart city benchmarking study is based on the benchmarking methodology (Ahmed & Rafiq, 1998; Anand & Kodali, 2008; Boxwell Jr, 1994; Carpinetti & Melo, 2002). Benchmarking has become a central instrument for improving the performance of the public sector and companies (Bogan & English, 1994; Spendolini, 1992). This development reflects that under the right conditions, comparison can be an important driver of better performance. Benchmarking should be seen as an evolutionary change management process (See e.g., Fernandez et al., 2001; Freytag & Hollensen, 2001) and action research processes can be linked to benchmarking process (see Kyrö, 2004; Kyrö & Tyrväinen, 2002). There is also a need to develop benchmarking culture and in the European Union benchmarking processes are seen to be an important challenge, because benchmarking can be seen as a precondition of cohesion and integration policy (See e.g., Biscop, 2007; Helgason, 1997; Zairi, 1994; Zairi & Whymark, 2000). Benchmarking is often seen to be linked to signalling, reputation, and cultural communications (See e.g. Bird & Smith, 2005; Certo, 2003; Nuñez, 2001; Piketty, 1998). Benchmarking can lead to benchlearning and finally to benchaction and many studies show and demonstrate positive results of this methodology (See e.g., Freytag & Hollensen, 2001). It is also possible to apply crowdsourcing methods in smart and regional development processes (See, Roth et al., 2013).

Benchmarking is based on the following key ideas: (1) Assess performance objectively, (2) create sustained pressure for improvement, (3) expose areas where improvement is needed and reveal underlying problems of an organisation or a group of organisations or network, (4) identify superior processes (5) focus on the links between processes and results, and (6) test whether improvement has been successful or not successful (See, Helgason, 1997; Kaufmann et al., 2003; Moriarty, 2011). All these six principles are relevant in the context of science, technology, innovation, education policy and decision-making.

Benchmarking is the practice of comparing business or country-level processes and performance metrics to units/countries' bests and best practices from other units/countries. Benchmarking is a process where you measure your country´s success against other similar countries to discover if there is a gap in performance that can be closed by improving your performance. According to Bogan & English (1994, p. 4) benchmarking is an on-going search and identification of best practices that produce superior performance when adapted and implemented in one's organization or network. Emphasis should be placed on the continuous elements of benchmarking, not just one-time comparisons, and benchmarking activities. Benchmarking is one of the key systemic governance mechanisms (Kaivo-oja & Stenvall, 2013).

It would be good if the different smart cities of the world were to compete to reach better performance in education and research of smart city developments. Benchmarking typically helps decision-makers to (1) identify strengths and areas for improvement, (2) facilitate the formulation of institutional development plans to build upon strengths and address the identified gaps, (3) prioritize STI policy interventions, and (4) monitor progress and achievements in science, education, and innovation policies. (See, Boxwell Jr, 1994).

3.4. Participatory Foresight Approach in the Smart City Digital Twin Project: A Methodological Approach

The fundamental reason why participatory foresight approaches were applied in the Smart City Digital Twin project was that participatory foresight processes have often several advantages like (1) diverse perspectives from different people and stakeholders, (2) diverse planning approaches of cities, (3) enhanced creativity and innovation capacity, (4) expected increased stakeholder buy-in and ownership, (5) efforts to improve decision-making capacity of city planning experts and professionals. (6) willingness to promote anticipation of emerging Issues and finally (7) needs relating to capacity building in smart city planning and know-how. Thus, there were many good reasons to apply participatory foresight process approaches.

Many city planning experts like Jan Gehl has underlined the importance of participatory processes in city planning (Gehl & Matan, 2009; Matan & Newman, 2019). He has noted that human-centered city planning is not possible without participation of individual citizens and experts with different backgrounds. He is a Danish architect and urban designer known for his work on human-centered urban design and the promotion of pedestrian-friendly cities. His approach emphasizes the importance of public spaces and community engagement in city planning. Also, Charles Landry, a British urbanist, author, and consultant has underlined that the role of culture is important urban development (Landry, 2017). Cultural aspects have impacts on foresight processes (See e.g., Kaivo-oja, 2017). Knowhow of local culture will be always needed also in smart city planning. In the field of futures studies, many European top experts like Joe Ravetz (Ravetz, 2020; Ravetz et al., 2020) have underlined the role of participatory foresight in urban and metropolitan planning.

By involving a wide range of stakeholders, including experts, policymakers, industry representatives, community members, and other relevant parties of city planning, participatory foresight processes can incorporate diverse participatory foresight perspectives. Many scholars expect that socio-cultural diversity helps in identifying a broader range of potential future scenarios and challenges. This aspect is important for innovation management too. When multiple stakeholders collaborate in a foresight exercise, it fosters creativity and innovation. Different viewpoints can spark new ideas and insights that might not have emerged in a more traditional, top-down hierarchical city planning approach. When stakeholders are actively engaged in the foresight process, they are more likely to feel ownership over the outcomes and be committed to implementing resulting local city strategies or actions. This can lead to greater buy-in and support for futures plans. Participatory foresight processes provide decision-makers a richer understanding of potential futures and also associated risks and opportunities. This can lead to more informed and robust democratic decision-making, as decisions can be based on a broader range of insights and inputs (Myllylä et al., 2012). Engaging stakeholders in foresight exercises can help build their capacity for strategic thinking, long-term planning, and anticipation of future trends. This can empower individuals and organizations to better navigate uncertainties and adapt to changing city circumstances. By bringing together diverse stakeholders to explore future trends and potential scenarios, participatory foresight processes can help strategies to address these issues before they become critical problems. Participatory foresight can be seen to be a pre-condition of democracy and "a medicine" against social apathy. Through participatory foresight exercises, organizations and communities can identify vulnerabilities and build resilience to future shocks and disruptions. By understanding potential future scenarios, stakeholders can better prepare for and mitigate the impacts of unforeseen events. (See e.g., Hilbert et al., 2009; Miles et al., 2003; Myllylä et al., 2012; Myllylä & Kaivo-oja, 2024).

To sum up, participatory foresight processes offer a holistic and inclusive approach to exploring the future, which can lead to more robust strategies, better decision-making, and increased resilience in the face of uncertainty and risks. Smart city planning should include various inclusive foresight processes to be impactful.

3.5. Case Study and Case Cities

In this smart city digital twin study, we apply case study methodology. A case study is one of the most commonly used methodologies of social research. A case study is a detailed study of a specific subject. Case studies are good for describing, comparing, analysing, evaluating, and finally understanding different aspects of a research problem (Priya, 2021; Yin, 2017). Case studies are commonly used in social, educational, clinical, and business research. We can learn much from special case studies. A case study is an appropriate research design when you want to gain concrete, contextual, in-depth knowledge about a specific real-world subject like smart city cases, in our special case contexts. It allows you to explore the key characteristics, meanings, and implications of smart city cases.

In case study research we might use just one complex case study where you explore a single subject in depth, or conduct multiple case studies (for example, many cities) to compare and illuminate different aspects of specific research problems. In general terms, we see many needs to develop case study programs of smart cities (See, Birch, 2012). A specific subject of the smart city planning process could be such as a person, group, place, event, organization, or phenomenon linked to smart city planning. In our case study, case studies are four special cities with special smart city planning approaches, Gdańsk, Wrocław, Vilnius, and Turku. A case study research design usually involves qualitative methods, but quantitative methods are sometimes also used. In our case city studies, we use also quantitative methods, to make some analytical comparisons of our case cities and apply the mixed methodology approach (See e.g., (Creswell J., 2014).

Each four city has a strategy that highlights its own objectives, visions and settings, demonstrating critical evidence on what above-mentioned scholars claimed (Kozlowski & Suwar, 2021; Neirotti et al., 2014; Toli & Murtagh, 2020; Yigitcanlar et al., 2018). In general, cities' strategies emphasis on environmentally responsible management is in line with dedication to sustainability, tackling an aging population, urbanization, and climate change as well as clear awareness of their advantages in innovation and urban management by emphasizing effective service delivery and technological advancement.

Table 7. Current Pillars in 4 Cities Smart City Strategies.

Brief Smart City Strategy Explanation	City
A smart city is an urban area that leverages technology to enhance the quality of life, infrastructure, environment, and services for its residents. It emphasizes the use of digital tools for efficient city management, economic growth, and sustainable living. The core idea is to create a connected, intelligent urban ecosystem that supports a high standard of living and fosters innovation.	**City of Wrocław**[2]
A smart city is a city that leverages digitalization and accumulated data to provide services independent of time and location, enhancing the productivity of city operations. "Smart and Wise City" strategy focuses on sustainable growth that supports well-being **(Wise City)** by enabling citizens and companies to utilize data for economic, social, and environmental benefits. The concept integrates strategies for being carbon neutral by 2029, service management, social inclusion, safety, traffic, mobility, and urban design to address challenges like climate change, urbanization, and an aging population.	**City of Turku**[3]
A smart city is an urban area that utilizes comprehensive solutions based on modern technologies to efficiently manage public spaces and improve the quality of life for its residents. It embodies the concept of an intelligent city by fostering effective, economical, and eco-friendly management, enhancing public services, mobility, energy, and citizen engagement.	**City of Gdańsk**[4]
A smart city is an urban setting that makes use of digital innovations to raise standards of living and efficiency and promote greater collaboration among its citizens. Vilnius is recognized for its technological advancements, such as real-time open-data and monitoring apps and efficient centres in such areas as financial technology, IT, biotechnology, electronics, innovation, and start-up hubs.	**City of Vilnius**[5]

The strategies laid out by Turku, Gdańsk, Vilnius, Wrocław show a shared vision for smart urban development that emphasizes the use of technology to improve many aspects of six-smart city dimensions. Considering the arguments in literature, these cities regulate a dedication pioneering the way in creating connected smart urban ecosystems that promote innovation, sustainability, and high living standards while fostering economic growth. By using digital technologies and an embrace of entrepreneurial innovation, they seek to address critical urban challenges and promote thriving, resilient communities.

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[2] Pillars of Smart City Wrocław (www.Wrocław.pl)
[3] Smart | Turun ja Varsinais-Suomen Eurooppa-toimisto (turkueuoffice.fi)
[4] Gdańsk's approach to a smart city (www.Gdańsk.pl)
[5] Smart City Solutions in Vilnius | Lithuania

4. INSIGHTS TO SMART CITY DIGITAL TWINS DEVELOPMENT

The project was completed with comprehensive up-to-date integrative literature review, mapping survey and engaged on-site foresight workshops held within four partner cities. The project's findings show a varied areas formed by limited participation in surveys and on-site foresight workshops. While acknowledging the importance of the insights gained from the 22 survey replies and the 433 recorded insights from the workshops, it is critical to emphasise the ethical issues and boundaries inherent in such a short foresight research project.

Survey respondents from Gdańsk, Turku, and Vilnius provided six, four, and six replies, respectively, while Wrocław and other areas contributed one and five responses. On-site foresight workshops had varying attendance: Gdańsk, 17; Wrocław, 22; Vilnius 41, but only five remained after introductory presentations; and Turku had 19 participants across two workshops on different days.

The relatively low number of participants limits reflection on the depth and breadth of insights gained, thus, provided quantitative analysis should not be interpreted as comprehensive evaluations of all aspects of each city. The quantitative analysis provided in subsections 4.1, 4.2., 4.3., 4.4., 4.5., and 4.6. is an attempt for methodological demonstration of how these insights might be used to inform future strategic foresight efforts.

While conducting our study, we carefully analysed the insights provided by the participants, who are experts in their fields and individuals and business representatives motivated about the project. Thus, while performing methodological demonstrations in subsections 4.1, 4.2., 4.3., 4.4., 4.5., and 4.6., we made sure to provide findings in line with the project's goal and scope, considering the small and diverse number of participants. Having reminded ourselves of our limitations and ethical considerations, future longer research should strive to reach a broader audience preferably subject-matter experts in cities, businesses, and research organizations as well as citizens who are motivated to be part of their city's SCDT development initiatives to enrich the depth of insights.

4.1. Mapping Survey Analysis

In this section, we present findings from the mapping survey. The survey received responses from 22 participants with various backgrounds and experience in SCDTs development. The responses to the questions were analysed based on three aspects of Futures Triangle Framework, each three addresses the essential components of the smart city digital twin settings in four case cities (see Appendix 1). Those three categories analysis derived from Futures Triangle framework are, *push of the present; pull of the future and lastly, weight of the past.*

City	Weight of the Past	Push of the Present	Pull of the Future
Turku	Cooperation challenges between public organizations and units in the city. Limited capacity and resources for development. Lack of joint vision and collaboration among civil servants. Strategy and goal alignment with resource allocation.	Developing a sustainable urban mobility plan, which a digital twin could support. Increasing demand for digital services. Interest in utilizing emerging technologies like AI and drones.	Citizens expect improved quality of life, sustainable solutions, and efficient digital public services. Visioning a comprehensive digital twin model for the city traffic. Enhancing citizen engagement, transparency, and service accessibility through digital twins.

According to four respondents, Turku encounters issues in collaborating within public and private organizations and needs a shared strategy for SCDT development. It seems that while limited financial resources, skills, and knowledge impede advancement, there is a push to include digital twins into their smart city services by utilizing developing technologies such as AI, IoT and drones. In the future, the city needs reassuring plans to fulfil citizen needs for digital services while also prioritizing involvement and transparent governance.

City	Weight of the Past	Push of the Present	Pull of the Future
Gdańsk	Conceptual understanding of SCDT challenges among stakeholders. Lack of awareness about SCDT possibilities. Need for concrete information based on former experiences. Limited data collection and processing capabilities.	New features and capabilities of advanced technologies. Focus on IoT, sensor and cloud technologies. Utilization of digital photogrammetry, 3D modelling and BIM applications. Incorporation of smart city solutions in urban infrastructure.	Enhancing citizen engagement and sustainability. Development of public and private sector partnerships. Prioritizing environmental sustainability in city planning. Adoption of advanced technologies for data-driven decision-making.

Six respondents noted in general that Gdańsk struggles to achieve consensus among stakeholders as it seems that there is also a need for practical knowledge based on first-hand experience. However, based on answers one conclusion might reveal that the city is continuously experimenting with new features and technologies, particularly in the public cloud, as well as using digital photogrammetry and BIM applications. Respondents also emphasise that Gdańsk strives to improve citizen involvement and promote environmental sustainability in city planning, as well as produce services for both the public and private sectors.

City	Weight of the Past	Push of the Present	Pull of the Future
Wrocław	Low level of communication. Financial constraints and funding issues.	Implementation of sustainable innovation strategies. Integration of emerging technologies in city operations. Adoption of AI, IoT, VR/AR, and cybersecurity solutions.	Building sustainable long-term cooperation models. Aligning state strategies with local development goals. Leveraging technology for efficient city management.

There was only one respondent who highlighted that Wrocław struggles with low administrative participation and little collaboration between public entities and research teams. Further, based on the answers respondent provided, financial restrictions and funding concerns further impede growth. Despite this, reported answers of respondent underline a current focus on developing long-term innovation plans and incorporating future technologies such as AI, IoT, and VR/AR into city operations.

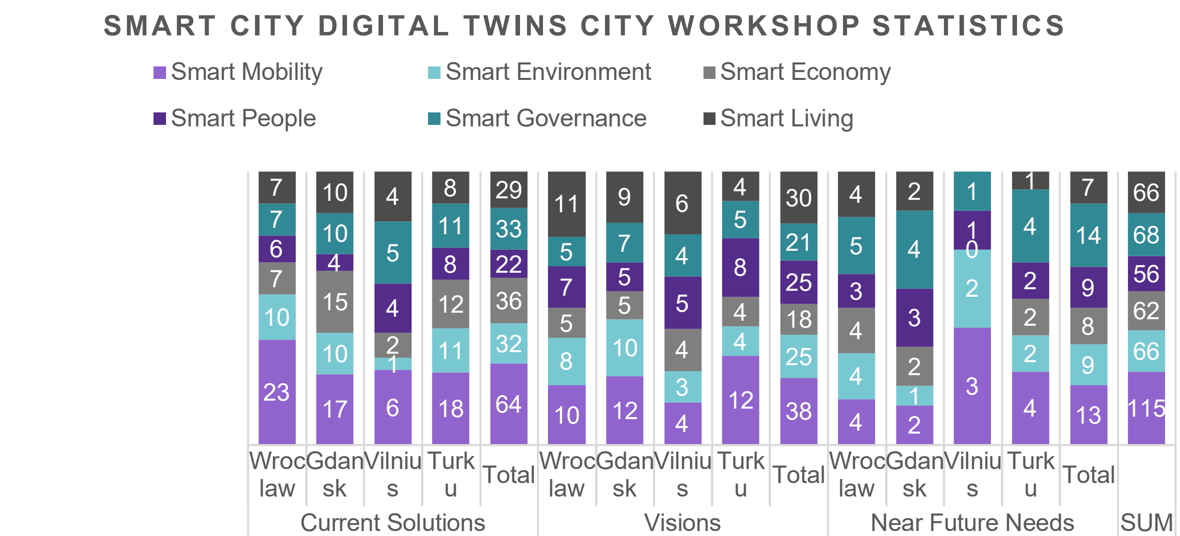
City	Weight of the Past	Push of the Present	Pull of the Future
Vilnius	Human and financial resource constraints. Community involvement challenges. Duration and capacity constraints in data processing. Technological limitations in hardware and software.	Vision for citizen-centric digital services. Utilization of digital twins for urban planning and development. Focus on improving quality of life and sustainability. 5G connectivity and AI-driven solutions.	Implementation of a comprehensive smart city master plan. Prioritizing real-time data collection and integration for informed decision-making. Collaborative efforts to enhance citizen engagement and transparency.

Finally, based on six respondents' answers from Vilnius, it seems that there are issues related to skills and financial resource restrictions, as well as community engagement. Furthermore, according to them there are constraints in data processing capability and duration while there is a clear vision for citizen-centric digital services and the use of digital twins in urban planning and development.

Despite participant numbers, the mapping survey might offer overall insights into the many aspects of SCDT development in case cities. From Turku to Vilnius, it seems that stakeholders are heavily invested in using new technology to address urban challenges and improve citizen well-being. While there is a noticeable drive to include digital twins into smart city services and infrastructure, problems such as funding boundaries, talent gaps, involvement of stakeholders, and technological limitations remain. Nonetheless, with a clear vision, coordinated efforts, and a focus on citizen-centric solutions, cities may overcome these difficulties and lead the way for a more sustainable, efficient, and inclusive urban future.

4.2. Foresight Workshop Insights

During foresight workshop in four case cities, participants added total 433 insights with 216 current solutions, 157 visions and 60 near future needs during workshop sessions (See Figure 21)



	Current Solutions					Visions					Near Future Needs					SUM
	Wroclaw	Gdansk	Vilnius	Turku	Total	Wroclaw	Gdansk	Vilnius	Turku	Total	Wroclaw	Gdansk	Vilnius	Turku	Total	
Smart Living	7	10	4	8	29	11	9	6	4	30	4	2	0	1	7	66
Smart Governance	7	10	5	11	33	5	7	4	5	21	5	4	1	4	14	68
Smart People	6	4	4	8	22	7	5	5	8	25	3	3	1	2	9	56
Smart Economy	7	15	2	12	36	5	5	4	4	18	4	2	0	2	8	62
Smart Environment	10	10	1	11	32	8	10	3	4	25	4	1	2	2	9	66
Smart Mobility	23	17	6	18	64	10	12	4	12	38	4	2	3	4	13	115

***Figure 21**. Foresight workshop insight statistics.*

The initial goal of assessing the insights obtained during these workshops on SCDTs development are twofold. The first is the conceptual understanding and comprehending cross-externalities of cities' current and prospective projects across six smart city domains, and the second is their maturity levels. For example, if a city is developing in a certain domain, it may be simpler for them to grasp the key technology requirements for meeting citizen and local demands by initiating digital twin development in that domain. Then, they can expand them to other domains. Cities will be able to develop concrete SCDTs solutions to be applied to other domains based on the knowledge obtained from digital twin technology integrations in domains with high maturity level.

In Fig 21., overall analysis reveals that Smart Mobility has the most insights, with 115 across all cities, Smart Economy and Smart Governance also have a strong presence, with 62 and 68 insights, respectively, and Smart Living and Smart Environment have an equal share of 66 insights among the cities.

Notably, compared to Smart Mobility, Smart People contain the fewest 56 insights, assuming that this might be an area for future improvement. Although all cities engaged on their SCDTs initiatives across six domains, analysis shows that cities have applications in place, particularly in the Smart Mobility domain, they might aim to take additional actions with digital twin integrations, considering their future mobility demands. Nonetheless, given the lower insights in the Smart People domain, cities might consider concentrating on building more citizen-centric smart mobility projects to facilitate SCDTs progress more.

As this overall analysis derived from foresight workshop participants provides a glimpse of the current state and future visions of these cities in their journey towards SCDTs developments. Also, quantitative analysis in Fig 21. can vary greatly depending on; (a) cities known or unknown unique challenges, resources, and priorities; (b) number of workshop participants and their involvement to the official city management and visionary strategy development activities; (c) participants' full-awareness on current smart city solutions and SCDTs initiatives in each city.

4.3. Smart City Wheel Analyses

Methodological Motivation to Percentage Analyses: Pareto Principle 80:20 in Urban City Planning

The Pareto distribution principle was developed by the Italian economist Vilfredo Pareto after studying the distribution of wealth in England in the early 1900s. According to observations, 80% of the wealth (cultivated land) was concentrated in 20% of the population (Pareto Principle 80:20). Since then, the Pareto principle has been shown to explain most real-life phenomena. Of course, the 80:20 ratio can vary somewhat depending on the phenomenon and its causes. In other words, if we do not estimate percentages of smart city digital twins development needs in the context of smart urban development, for example, we cannot estimate the possibility of a Pareto Principle distribution in the context of urban development. In the context of smart city development, the hypothesis may be that 20% of smart elements (smart city digital twins) produce 80% of the functional beneficial elements of a smart city. This means that one smart city wheel element or two critical smart city wheel elements may stand out more clearly than others. If there is no clear difference in dominance in importance, the Pareto principle does not work in this special smart city case. In most cases, it is expected to hold even in important urban development contexts (Bookstein 1990, Rosen et al. 1980). See an example of how histograms can be used in the special case of economic growth (GDP) and regional carbon dioxide emissions management (see Kaivo-oja et. al 2023).

The percentage measures the share of different sectors (six different smart city wheel parts) in the total shares. This metric gives you an overall picture of how experts are allocated to different areas of the smart city wheel. In strategic appraisal, the estimation of percentages often plays a key role in the strategic selection of priorities. For example, a classic example of the importance of percentage points is an assessment based on the Pareto criterion. The Pareto Principle can be applied to a variety of situations, including business, economics, city planning, service planning, quality control, and the field of prototyping (see e.g. Rosen and Resnick 1980), Bookstein 1990, Reed

2001, Klass et al. 2006, Pandey et al 2013). The Pareto Principle is often touted as a powerful tool for productivity and business management. When selecting strategic key digital twins (potential "20%" digital twins, it is wise to consider the potential 20/80 Pareto Rule to find potential "80" with impacts on citizens. If we are not analysing the percentage distributions of potential smart city digital twin layers, it is not possible to discuss these important issues. Neglecting percentage distribution questions can be a very costly activity for urban citizens.

Testing the potential distribution of smart digital twins can help cities in the productivity development of city services and digital twin development. When used correctly, the Pareto Principle can help prioritize tasks, optimize resources, and improve overall efficiency in the smart city planning process. It provides a useful framework for understanding complex systems and identifying key areas for potential improvement. The Pareto principle means that in any phenomenon the majority (about 80%) of the consequences are due to a small part of the causes (about 20%). This statistical basic analysis is done typically by statistical histograms and synergy analyses (see e.g. Kaivo-oja et. al 2022, Kaivo-oja et al. 2023).

In interpreting the Pareto principle this mean that we should pay more attention to high percentages wheels of Smart City Wheels than low percentages of Smart City Wheels. However, caution should be exercised in interpretations, because the data was small, as we have already noted above. This research section is pilot-like in nature.

Smart City Wheel Analysis of Current situation: Results from Case Cities

In Figure 22 we report current situation analysis of Smart city wheel domains in the city of Wrocław. This figure reveals that the strongest domain in Wrocław was evaluated to be smart mobility domain. Other smart city wheel domains were evaluated to be moderately strong. Strong environment domain was evaluated to be second strongest by experts.

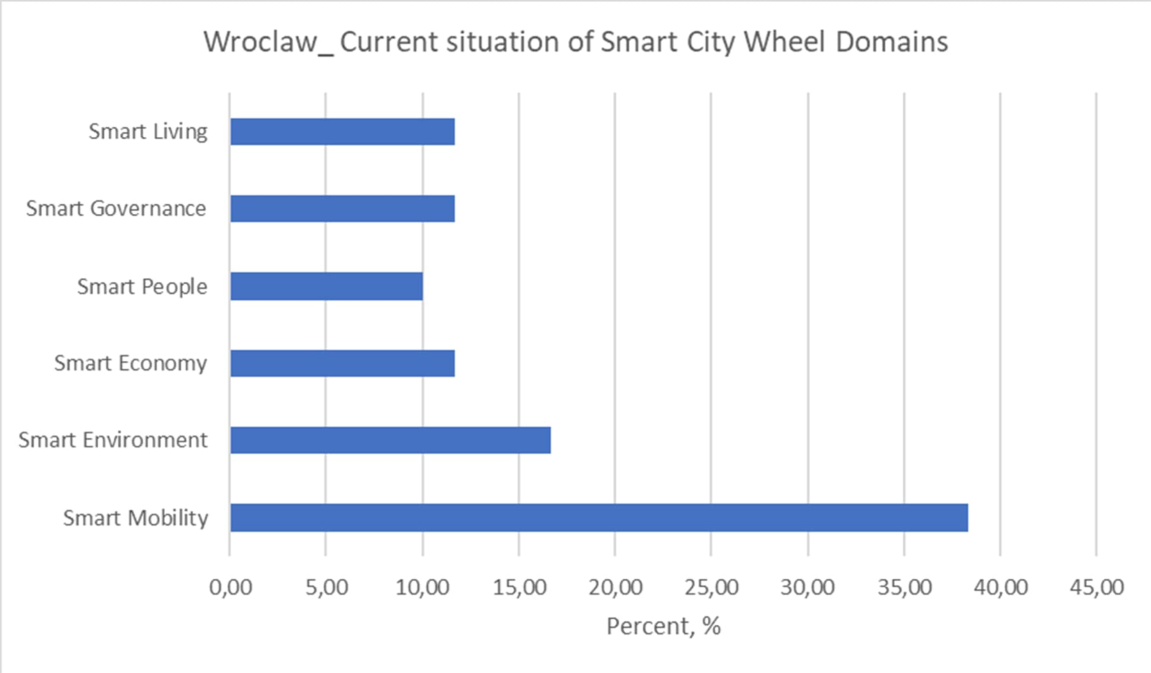


Figure 22. *Wrocław: Current situation of Smart City Wheel domains.*

In Figure 23 we report current situation analysis of Smart city wheel domains in the city of Gdańsk. This figure reveals that strongest domain in Gdańsk was evaluated to be smart mobility domain. Other strong domains were evaluated to be smart economy. Weakest domain was evaluated to be smart people. Quite strong domains were evaluated to be smart living and smart government. The environment domain was evaluated to be second strongest by experts.

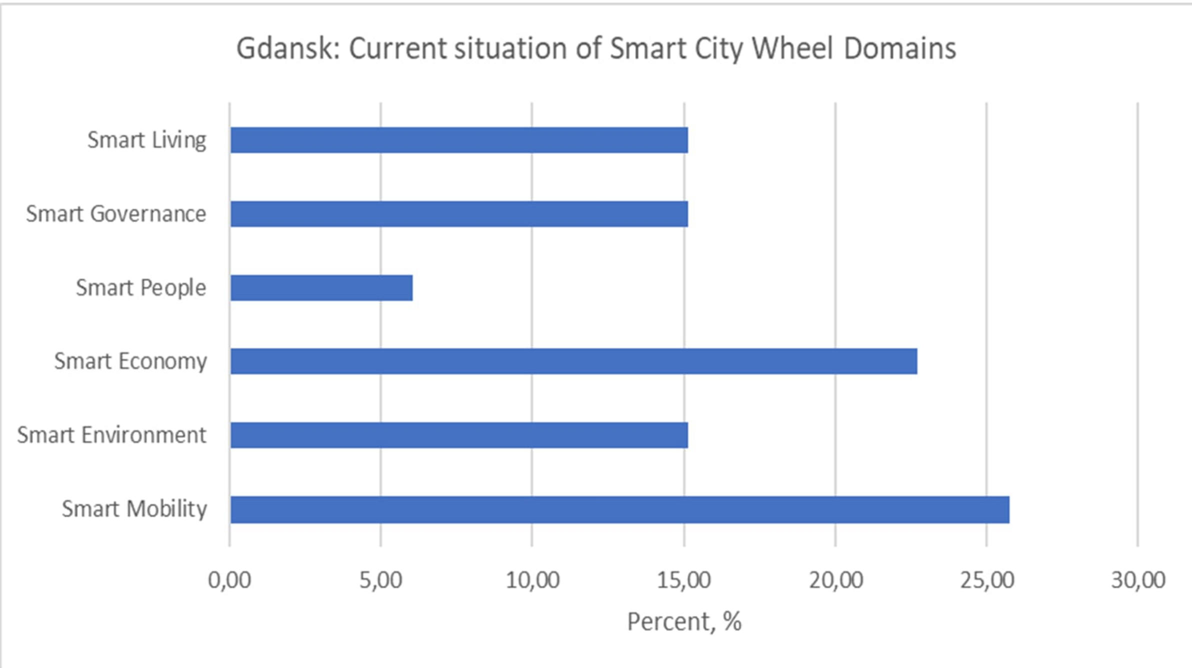


Figure 23. *Gdańsk: Current situation of Smart City Wheel domains.*

In Figure 24 we report current situation analysis of Smart city wheel domains in the city of Vilnius. Again, the strongest domain was evaluated to be smart mobility. The weakest domain was evaluated to be smart environment in Vilnius. Second best domain was smart governance while smart living and smart people were evaluated to be on a moderate level. The smart city wheel domain of smart economy was second weakest smart city wheel development domain.

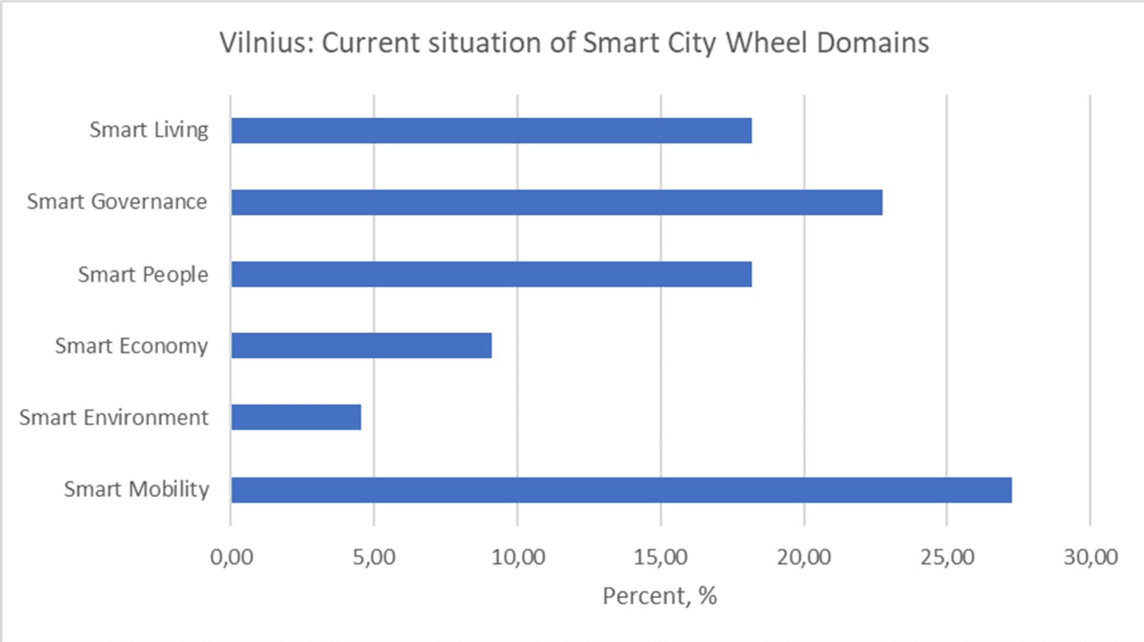


Figure 24. *Vilnius: Current situation of Smart City Wheel domains.*

In Figure 25 we report current situation analysis of Smart city wheel domains in the city of Turku. Again, the strongest domain was evaluated to be smart mobility. Other domains were evaluated to be on moderate medium level levels in current situation. Very critically, smart people domain was evaluated to be the weakest. In an academic university city, this result is quite interesting.

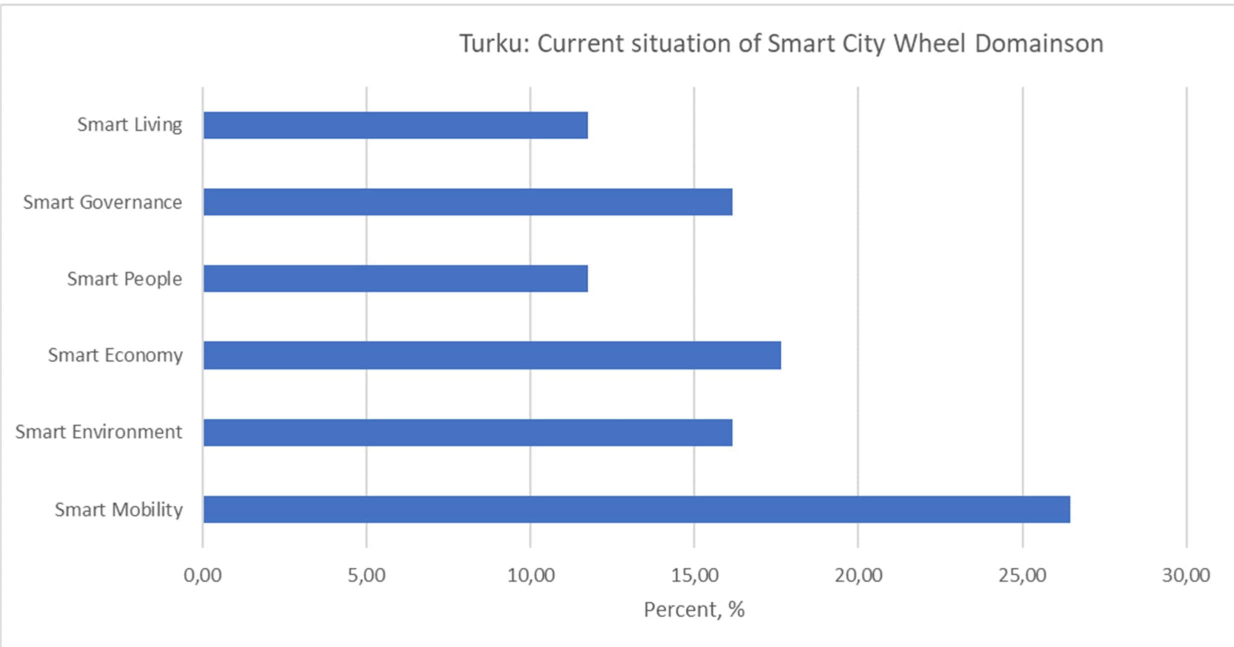


Figure 25. *Turku: Current situation of Smart City Wheel domains.*

4.4. Smart City Wheel Analysis of Needs of Near Future Situation: Results from Case Cities

Next, we analyse the smart city wheel results of near future needs. In Figure 26 we report near future needs analysis of Smart city wheel domains in the city of Wrocław. This figure reveals that strongest domain of near future needs in Wrocław was evaluated to be smart governance domain. Other smart city wheel domains (smart living, smart economy, smart environment, and smart mobility) were evaluated to have need moderate medium level development needs in city planning. In Wrocław smart people domain were evaluated by experts to need the weakest development attention in smart city planning processes in near future.

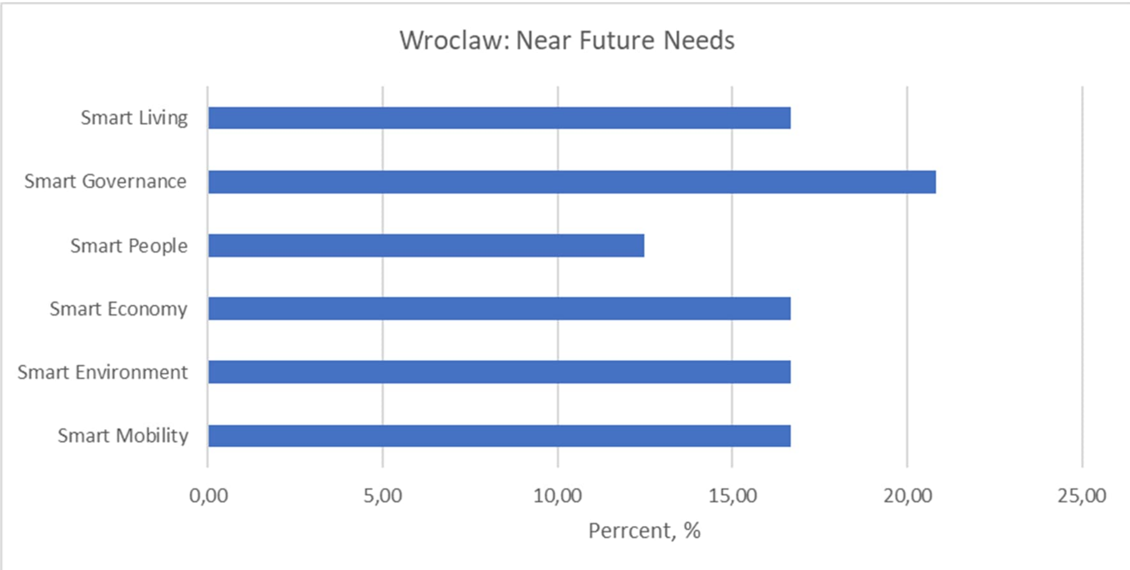


Figure 26. *Wrocław: Near future needs of Smart City Wheel domains.*

In Figure 27 we report near future needs analysis of Smart city wheel domains in the city of Gdańsk. This figure reveals that strongest domain of near future needs in Gdańsk was evaluated to be smart governance domain and second development field was evaluated to be smart people domain. Other domains (smart living and smart economy were evaluated to have moderate needs for development. In Gdańsk, smart environment domain was evaluated by experts to need the weakest city development attention in near future.

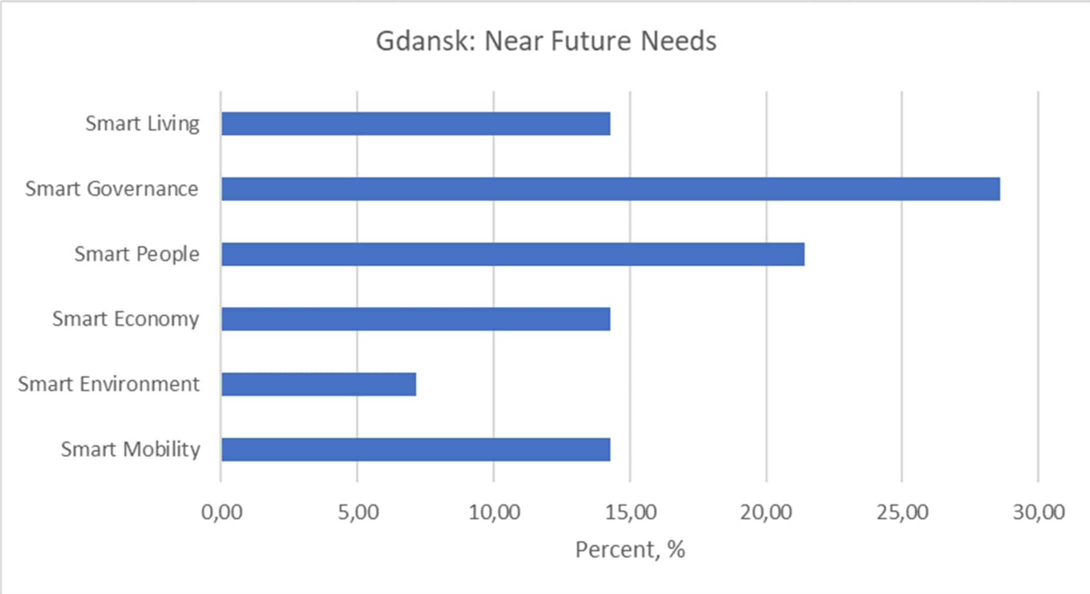


Figure 27. *Gdańsk: Near future needs of Smart City Wheel domains.*

In Figure 28 we report near future needs analysis of Smart city wheel domains in the city of Vilnius. The strongest domain to be developed were evaluated by experts to be smart mobility and after smart mobility, second strongest development need domain is smart environment. The weakest domain for further development needs was evaluated to be smart economy and smart living in the city of Vilnius. The domains of smart governance and smart were evaluated to need some moderate, medium level attention in the future.

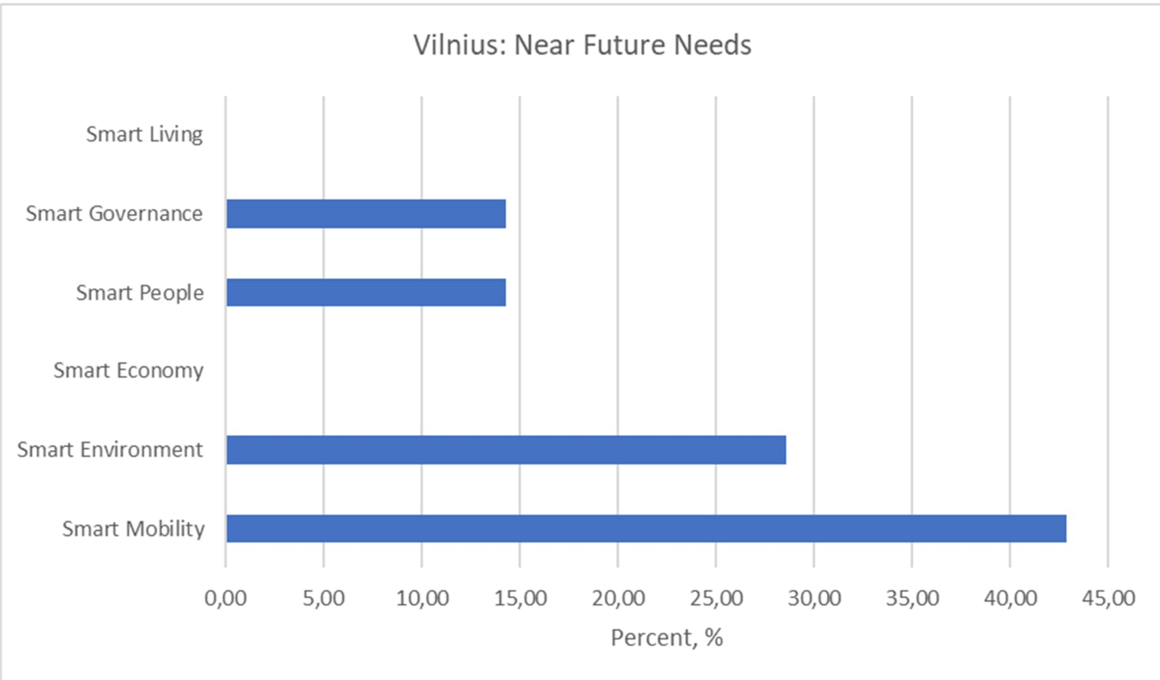


Figure 28. *Vilnius: Near future needs of Smart City Wheel domains.*

In Figure 29 we report near future needs analysis of Smart city wheel domains in the city of Turku. The strongest domain to be developed were evaluated to be smart mobility and smart government. The weakest domain for further development needs was evaluated to be smart living. The domains of smart people, smart environment and smart economy were evaluated to need some moderate, medium level attention level in the near future.

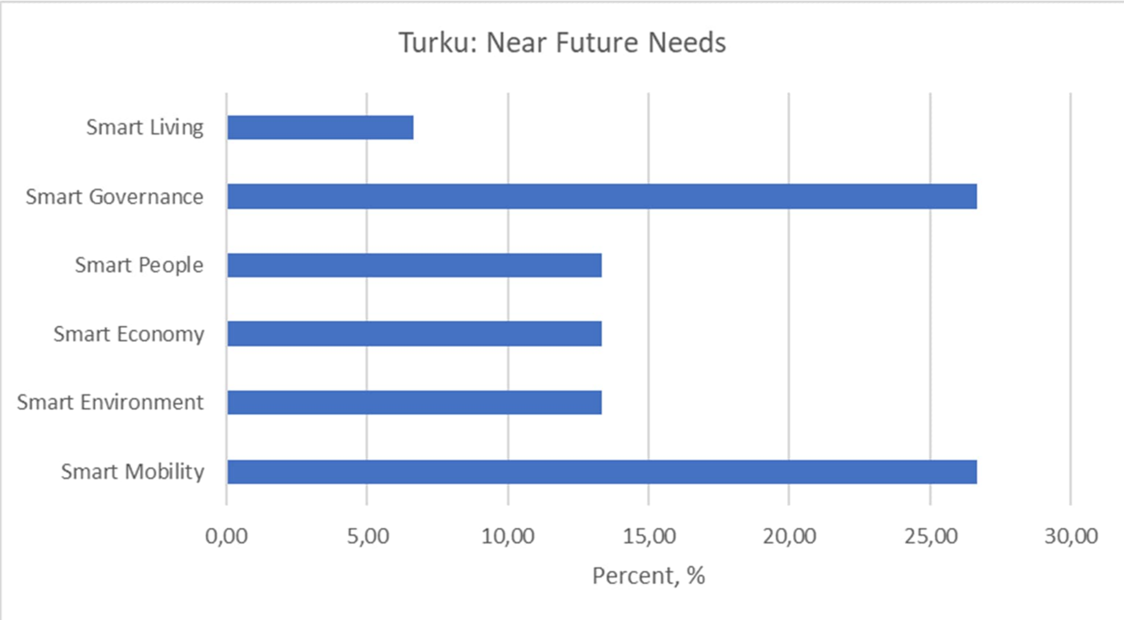


Figure 29. *Turku: Near future needs of Smart City Wheel domains.*

4.5. Smart City Wheel Analysis of City Visions: Results from Case Cities

Next, we analyse the results and findings of smart city wheel analyses of long run visions. In Figure 30 we report long-run vision analyses of Smart city wheel domains in the city of Wrocław. This figure reveals that strongest domain of long-run vision in Wrocław was evaluated to be smart living domain. Secondly important domain was evaluated to be smart mobility. Other domains (smart environment and smart people) were evaluated to have moderate needs in the long run. Weakest long run development needs were evaluated to be in the domains of smart economy and smart government.

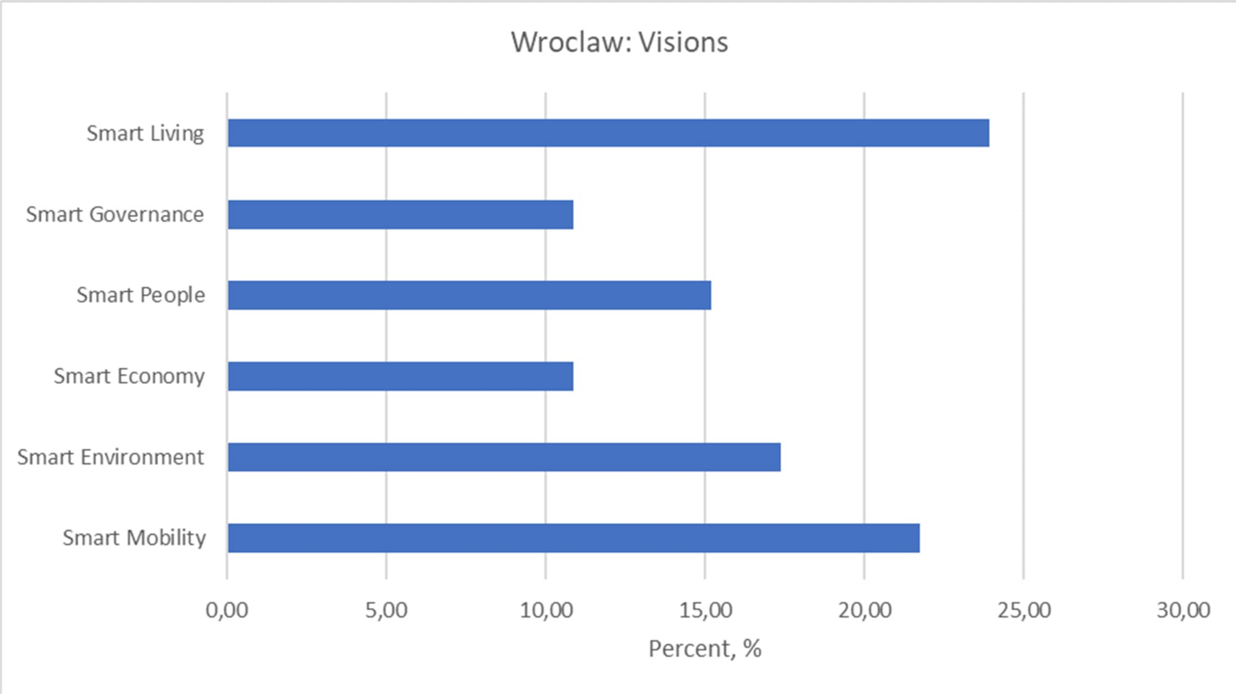


Figure 30. *Wrocław: Long-run vision analysis of Smart City Wheel domains.*

In Figure 31 we report a long-run vision analysis of Smart city wheel domains in the city of Gdańsk. This figure reveals that strongest domain long-run development in Gdańsk was evaluated to be smart mobility domain and second development fields were evaluated to be smart living domain. Other domains (smart environment and smart government) were evaluated to have moderate needs for development. In Gdańsk, smart people and smart economy domains were evaluated by experts to need the weakest long-run visionary development attention.

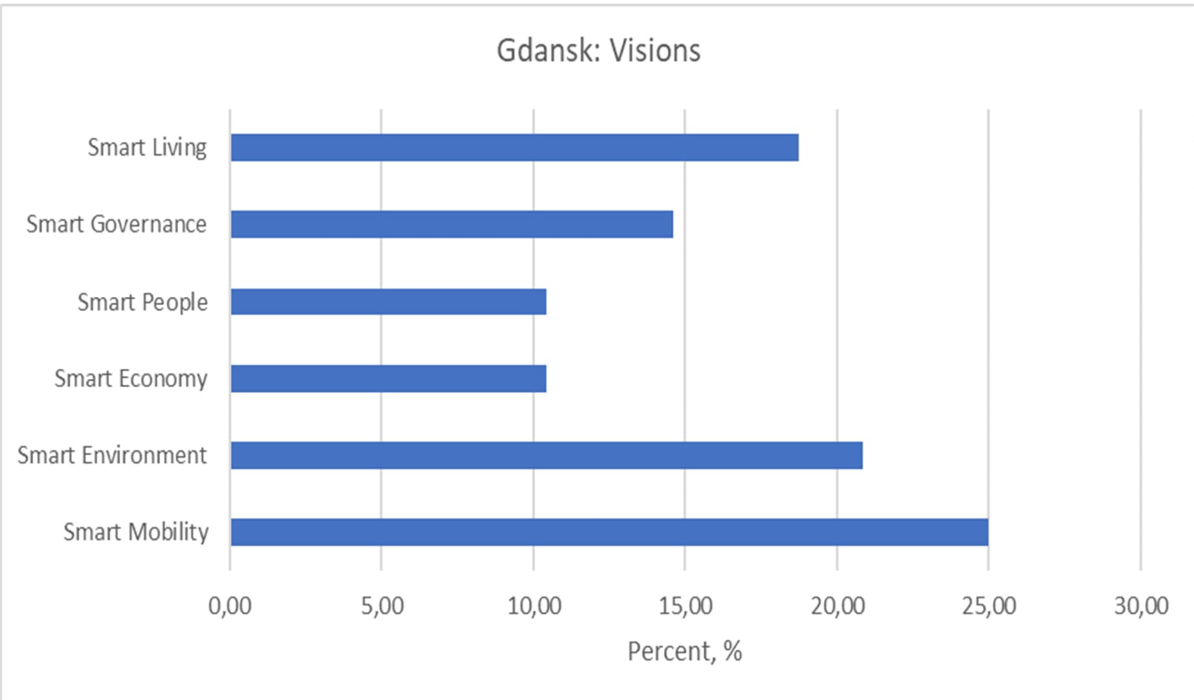


Figure 31*. Gdańsk: Long-run vision analysis of Smart City Wheel domains.*

In Figure 32 we report a long-run vision analysis of Smart city wheel domains in the city of Vilnius. This figure reveals that the strongest domain long-run development in Vilnius was evaluated to be smart living domain. After this second priority were evaluated to be smart people domain of smart city wheel. The lowest priority domain was evaluated to be smart environment in Vilnius. Moderate important domains of long-run visionary smart city development were smart government, smart economy, and smart mobility.

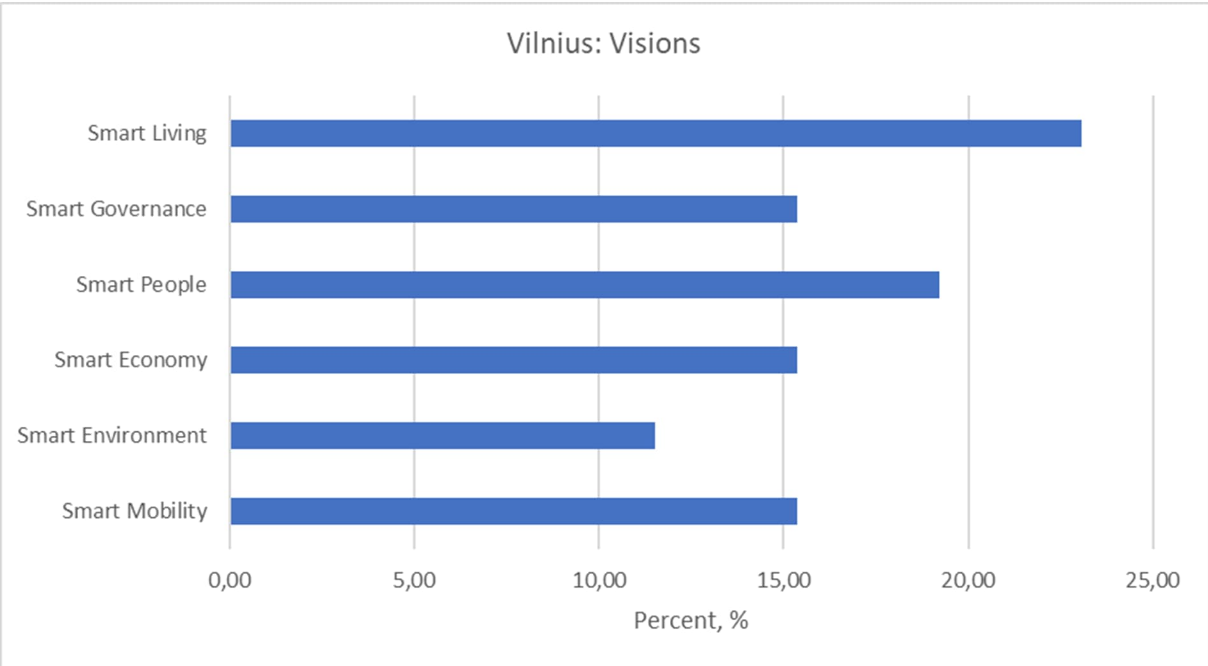


Figure 32. *Vilnius: Long-run vision analysis of Smart City Wheel domains.*

In Figure 33 we report a long-run vision analysis of Smart city wheel domains in the city of Turku. This figure reveals that the strongest domain in long-run development in Turku was evaluated to be smart mobility domain. The second priority domain in long-run development work was smart people domain of smart city wheel. Other key three domains of smart city wheel elements are smart living, smart economy and smart environment which gained similar balanced assessments of experts.

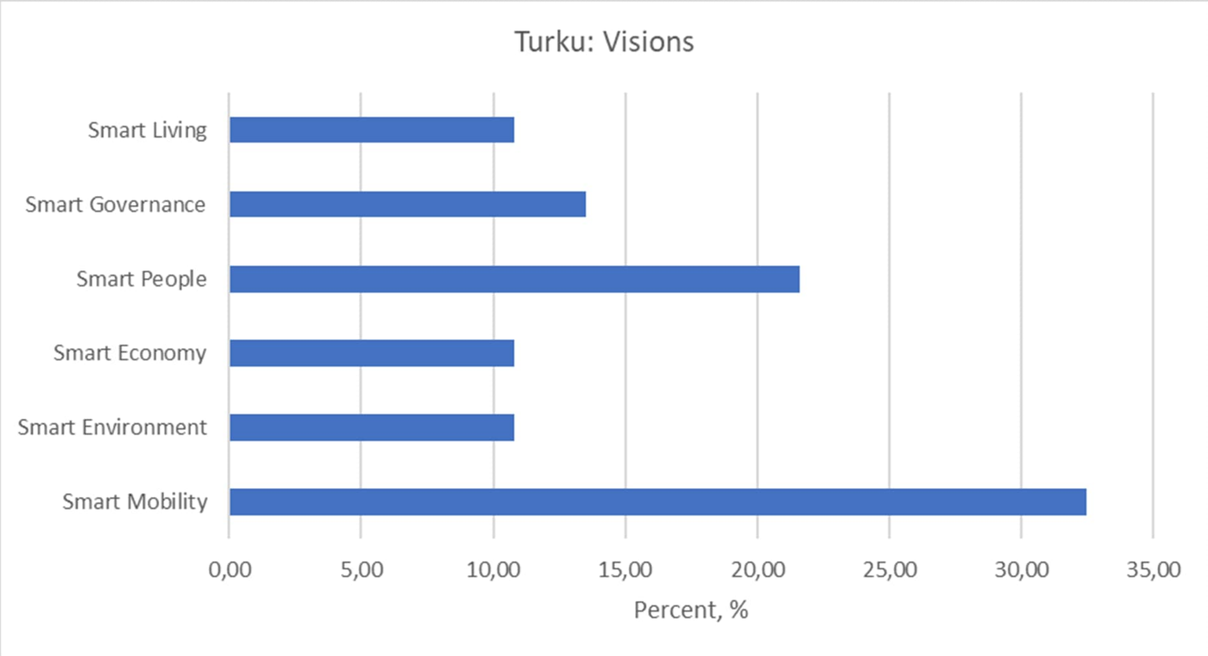


Figure 33. *Turku: Long-run vision of Smart City Wheel domains.*

4.6. Futures Tensions Analyses of Case Cities

In Figure 34 we report tensions analyses of future situations and current situations, and tension between near future and future vision in Wrocław. There seems to the strongest tensions in smart mobility planning. The weakest tensions are associated with smart environment domain. Quite strong tensions are associated with smart government.

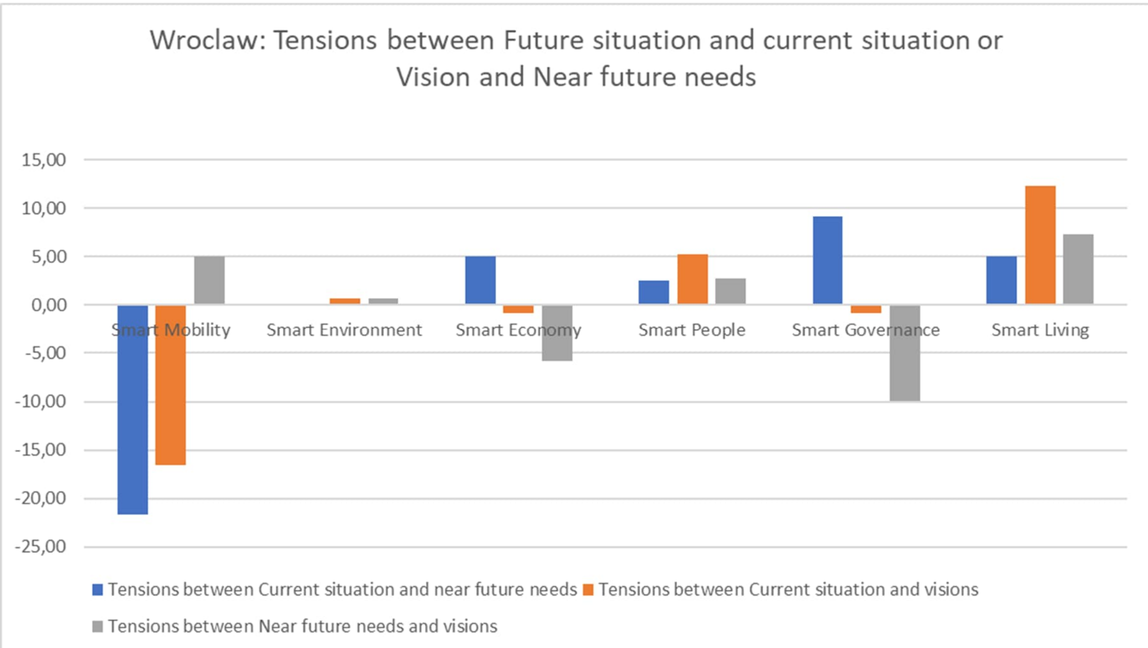


Figure 34. *Wrocław: Tensions between Future situation and current situation or tension between Vision and Near future needs.*

In Figure 35 we report tensions analyses of future situations and current situations and tension between near future and future vision in Gdańsk. There seems to the strong tensions in smart environment and smart economy planning. The weakest tensions are associated with smart living domain. Quite strong tensions are associated with other smart city wheel domains.

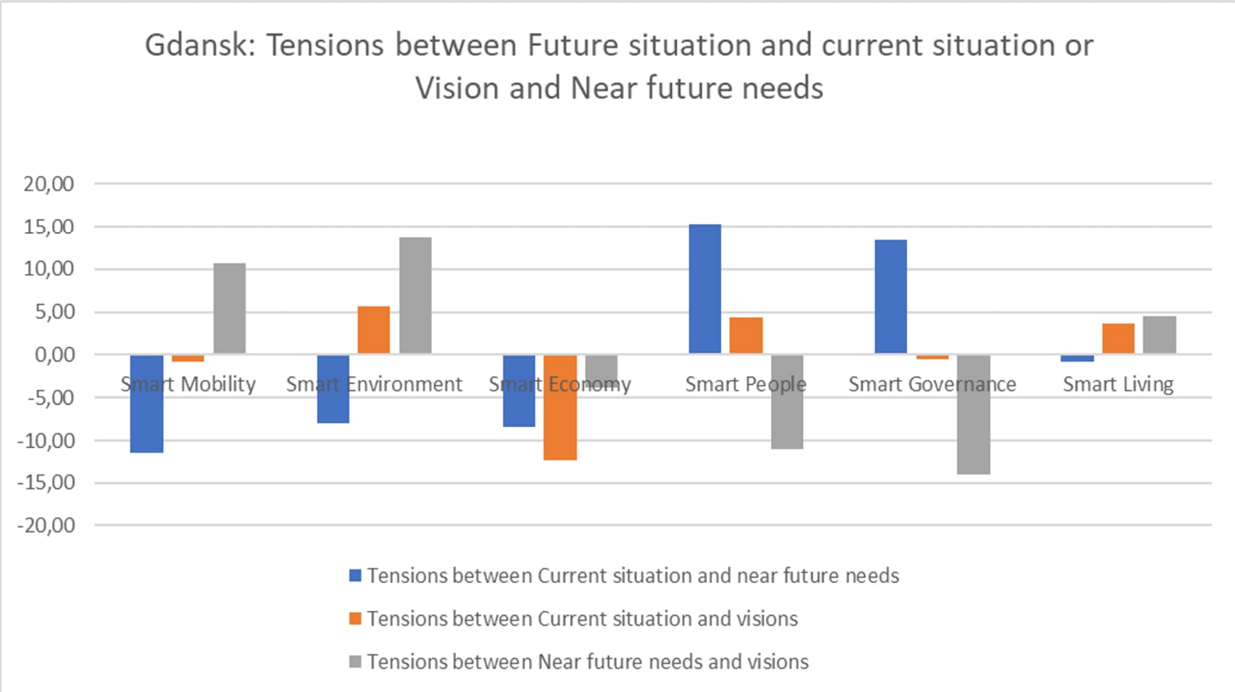


Figure 35. *Gdańsk: Tensions between Future situation and current situation or tension between Vision and Near future needs.*

In Figure 36 we report tensions analyses of future situations and current situation, and tension between near future and future vision in Vilnius. There seems to the strong tensions in smart mobility, smart environment, smart economy, and smart living domains of smart city wheel. Less serious tensions can be identified to be in smart people and smart government domains.

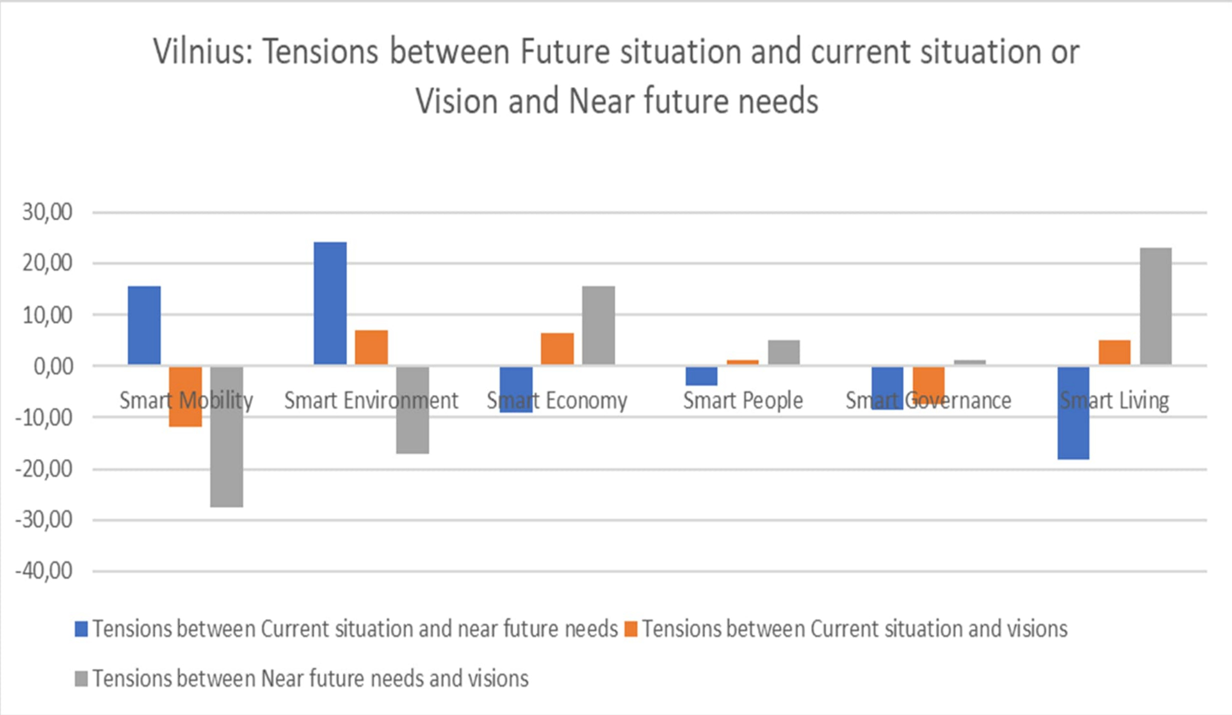


Figure 36. *Vilnius: Tensions between Future situation and current situation or tension between Vision and Near future needs*

In Figure 37 we report tensions analyses of future situations and current situations and tension between near future and future vision in Turku case. There seems to the strong tensions in smart government, smart people, and smart living domains of smart city wheel in Turku case. Lowest domain tensions were identified in smart environment and smart mobility.

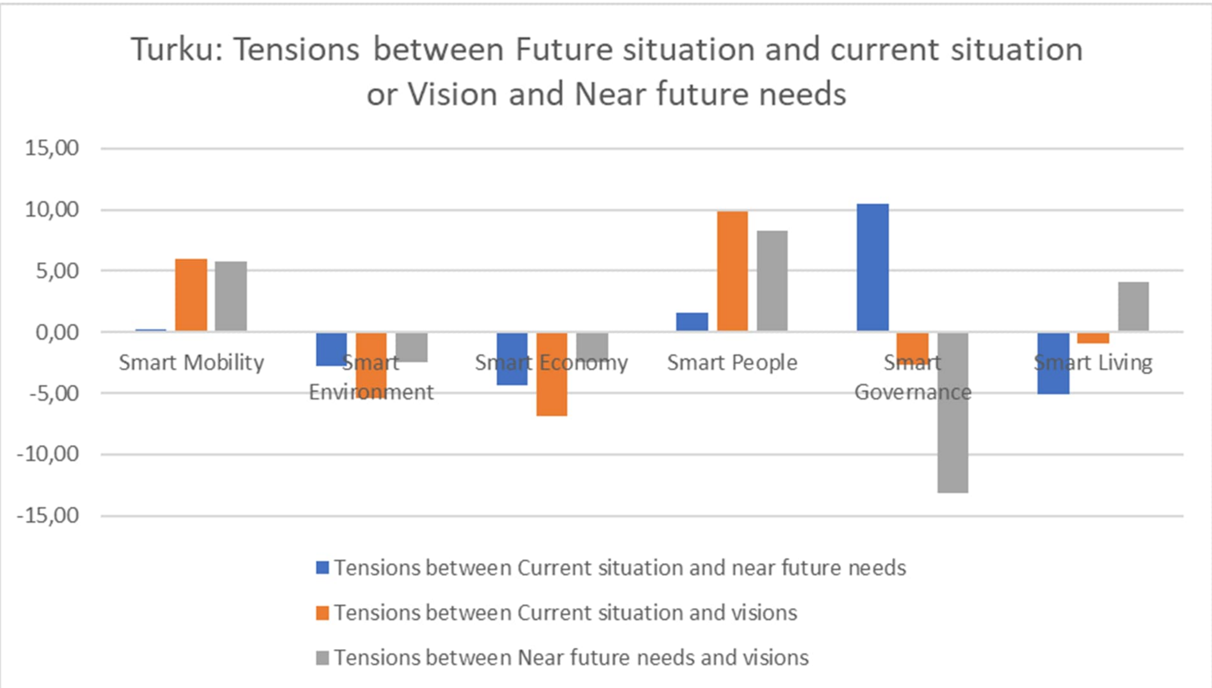


Figure 37. *Turku: Tensions between Future situation and current situation or tension between Vision and Near future needs.*

The findings and results presented in this section on the current, near-term and long-term smart urban development priorities of cities clearly highlight the need for careful evaluation of smart urban development processes. The Smart City Wheel method is an interesting and useful tool in this sense. The different results and priorities of smart city wheel assessments indicate that cities need to discuss smart urban development priorities carefully. An important conclusion is that it does not make sense to directly copy smart city development strategies from other cities. Smart city strategies must be tailored and rooted to local city planning challenges.

4.7. Overview Analysis on Case Cities' Current Pillars on Smart City Strategies

The smart city approaches of the four cities subject to the report in general, we see the signs of articulation of the smart city trends and initiatives to their smart city strategies. (See Table 7)

When we look in detail at the approaches such as innovation, initiative and liveability, which four case cities conceptually articulate to smart city strategies, it is worth to remind critical perspectives on these labelling efforts drawn by scholars assessing them "self-congratulatory" (Hollands, 2008, p. 304) and "superficial" (Caragliu et al., 2011, p. 69). Based on this critical approach, Lombardi et al., (2012) developed a framework including 60 indicators to model, cluster and measure the performance of smart cities demonstrating which level they are on being smart and – 'Entrepreneurial City', 'Pioneer City', 'Liveable City' and 'Connected City'. They outline those concepts as follows (Ibid 2012, p. 147);

Entrepreneurial City: In the current and future global and local competition, this concept explains how a city may compete in both local and international markets by making the most of its inventive and creative capabilities. It acknowledges cities as key to Europe's globalization strategy, serving as gateways to developing markets outside of the continent. To establish itself as a vibrant centre for trade and investment, the entrepreneurial city supports an atmosphere that encourages entrepreneurship, innovation, and economic growth.

Pioneer City: The innovative and culturally diverse nature of future metropolitan regions can be seen by the pioneer city. It foresees hitherto unheard-of levels of cultural diversity and fragmentation of lifestyle, posing both possibilities and difficulties for smart and innovative enterprises. According to this concept European cities may be worldwide leaders in innovation by valuing variety and creating atmospheres that promote experimentation, collaboration, and sharing of ideas.

Liveable City: The concept highlights how cities may become agents of ecological sustainability rather than just being energy consumers and environmental pollutants. Cities might implement energy and environmental programs like waste recovery and recycling to become climate-neutral players in the emerging space economy. To provide people with appealing and sustainable living and working environments, the liveable city places a high priority on the preservation of the ecological diversity.

Connected City: It emphasizes how linked today's world is and how important it is for cities to get integrated into larger networks to thrive economically and socially. Cities need to make use of advanced mobility networks, intelligent supply chain management strategies, and easily available communication channels to prosperity. Connected cities increase their resilience and competitiveness in the global economy by acting as hubs or nodes in polycentric networks, such as information and innovation networks.

'Wise City', another concept that should be emphasized since it is prominent and the only articulated by City of Turku as 'Smart and Wise City' strategy.

Hambleton (2021, p. 54) define "Wise City" as

"[…] advances in ICT can, in my view, make an important contribution to improving the quality of governance and urban governance. But to do this, the focus of attention needs to be on "**judgement"**. Acquiring zettabytes, or even yottabytes, of data about human and technical interactions in cities is not going to enhance the quality of life in cities in the absence of **"wise judgement"** about what really matters. Judgement involves thoughtful consideration about future possibilities. It needs to be informed by sound values, it requires imagination and creativity, and, in a democratic society, it needs to be underpinned by inclusive, participatory decision-making processes […] To address challenges successfully, we may need to step beyond traditional smart cities thinking and pay more attention to how to co-create wise cities."

Narsungbhai & Padhya (2022, p. b37) bring holistic perspective to Wise City concept with,

"[…] the Wise City concept helps to coordinate all interdisciplinary research disciplines in the complex ecosystem of the city and organize the science of the city in one framework. A human-cantered approach, resilience, techno-culture, trust building, quadruple helix, experiential learning, and broad identity are wise urban principles." and outline 9 principles aligning with 22 indicators of being Wise City by reminding cities to avoid 'one-size fits all' trajectories.

The Wise City is characterised by the following nine principles (Narsungbhai & Padhya, 2022, p. b35–b36):

1. People-centred approach: Citizens' well-being is at the centre of policymaking. Public opinion and participation are required at every stage of planning.

2. Resilience: Tailored to the unique cultural characteristics, socioeconomic situation, environmental conditions, and general sustainability of each city. The "one for all" approach has been repeatedly shown to be incorrect, thus it is imperative to handle each city according to its unique characteristics while adhering to the ideal principles of a smart city.

3. Techno-culture: Technology to enhance the welfare of people. Given that technology has had the worst effects in highly technologically advanced cities, it is critical to realize that technology use should be optimized and that features geared toward the needs of children and the elderly should be developed.

4. Quadruple Helix: Collaboration between public and private sectors to integrate and involve stakeholders (people, government, businesses, academics). Including educational institutions in the relevant subject and fostering healthy competition will result in creative planning concepts.

5. Trust-building: Stakeholder participation will lead to the development and strengthening of social capital. There will be a focus on inclusive development.

6. Experiential Learning: Benchmarking and keeping an eye on and assessing regulations and exchanging experience-based information (both domestically and internationally). This stage will assist in determining the optimum development strategy due to differentiation.

7. Brand Identity and Reputation: Implementing locally appropriate solutions and creating a brand that may serve as an inspiration to other cities and planners.

8. Coordination: Establish regular communication between the various departments. This can guarantee efficient and seamless development across several departments.

9. Revamp Corporate Government Structure: To improve operational autonomy while strengthening good governance practices, such as going public on a stock exchange to increase accounting and transparency.

These criterion and performance-assessment tools on current pillars can be considered in detail and shed light on the concepts that the four cities have added to their smart city approaches. So that the concepts put forward in strategies can be underlined. On the other hand, in addition to these city-specific enlightening literatures, it is important for cities to consider high standardization and benchmarking studies with high reputation and binding in the smart city paradigm, which aims to measure the smart city performances of cities at the international level.

Gdańsk

The findings from the Gdańsk Workshop shed light on the city's present achievements as well as its future goals in relation to Smart City Digital Twins (Figure 38). Gdańsk is firmly committed to leveraging digital technologies for urban development, as evidenced by the several projects it is presently pursuing to advance sustainability, innovation, and effective governance as well as standardization initiative. For example, as a result of our general analysis, it was reported that Gdańsk is the only city with ISO 37120 standardization initiative compared to the other three cities (Gdańsk Certyfikat Został Przyznany w 2017 Roku, 2023). The city's emphasis on environmental sustainability, enhanced mobility, efficient governance, and economic development is in line with the larger objectives of smart cities, which include using technology to improve the standard of living for citizens by Smart City Digital Twins.

	CURRENT SOLUTIONS	NEAR FUTURE NEEDS	VISIONS
GDANSK POLAND	• Waste management and monitoring systems. • Autonomous transportation options. • Various economic project fundings.	• Need for interconnected transport options. • Parking improvements. • Air, soil, and water monitoring. • Sustainable start-up ecosystem. • Focus on ethical AI and data governance.	• Visions include reducing carbon emissions, enhancing automation, and promoting green solutions. • Transition to a smart, connected city with autonomous transportation. • Shift towards digital payments and services. • Creation of unified systems for city living and governance.

Figure 38. *Key insights from the Gdańsk workshop.*

The insights also show that Gdańsk, like many other cities, struggles with planning for unexpected disruptions and imagining other possible futures. Gdańsk needs to make investments in adaptive, flexible solutions that can flourish in a range of future scenarios if it is to fully realise the potential of Smart City Digital Twins. As the city acknowledges the enduring impact of a traditional Eastern European attitude, it is also imperative to address cultural and mindset adjustments. The key to effectively implementing digital transformations will be adopting a mindset that embraces innovation and the larger picture.

The discussions emphasized that in the near future "mental change" will be the cornerstone of smart city digital twin projects. It is imperative to encourage a change in the way individuals view technology and the opportunities it offers for their everyday lives. The city can set the stage for a "smart city" where digital twin enabled digital solutions improve every area of life in the future Gdańsk "smart society" by starting with "smart parents" who recognize the importance of technology in "smart home" and in "smart schools." Creating long-term plans that can adjust to changing conditions should be Gdańsk's top priority to address the problem of narrow-mindedness and transient political goals. In doing so, the city can ensure that its journey towards becoming a smart city is characterized by adaptability, resilience, and a commitment to the well-being of its residents.

Furthermore, more insights for each dimension and each theme should be gathered. Current Solutions, Visions and Near Future Needs, In the context of Smart City Digital Twins in Gdańsk, several key themes emerge to be pondered on in near future.

Sustainability and Environmental Quality: Gdańsk should continue its focus on sustainability, striving to reduce emissions, promote recycling, and improve air, water, and noise quality. The city needs comprehensive monitoring systems to ensure the environmental goals are met and the local population enjoys a high quality of life.

Efficient Mobility: Improving urban mobility is crucial, which includes expanding public transportation, implementing smart traffic solutions, and embracing sustainable transportation modes such as bikes and e-scooters. Gdańsk needs a comprehensive approach to transportation that offers unified ticketing systems and reduces traffic congestion, contributing to improved mobility for residents.

Digital Transformation and Governance: The city should transition to digital government institutions, streamlining services, and providing efficient digital communication channels. Ensuring a decentralized and transparent governance structure will be essential, allowing for well-informed decisions based on data-driven insights.

Resilience and Future-Readiness: Gdańsk needs to foster a culture of innovation and preparedness for unexpected disruptions, as evidenced by the need for more comprehensive responses to "what-if" scenarios. The city should continue to develop flexible and adaptable solutions that can withstand and recover from various future uncertainties.

Community Involvement: Encouraging the active involvement of citizens in decision-making processes is crucial. The "citizen budget" concept is a step in the right direction. Promoting initiatives that bring neighbours and the community together will foster a sense of ownership and participation in the city's development.

Digitalization and Change Management: A "mental change" is needed to shift the mindset of both the population and political systems toward embracing digitalization. Strong public institutions and change management strategies are necessary to support the digital transformation.

Interconnected Urban Planning: The "15-Minute City" concept and the emphasis on interconnected urban planning are integral for creating walkable, convenient, and sustainable neighbourhoods. Gdańsk should focus on creating smart destinations that provide residents with easy access to essential amenities within a close radius.

Public-Private-People Collaboration: Encouraging wide-scale collaboration among all stakeholders, including politicians, companies, the public sector, volunteers, and citizens, is critical in the development of Smart City Digital Twins.

In summary, Gdańsk needs to continue its efforts in sustainability, mobility, governance, and community involvement while fostering innovation and resilience to effectively transition to the era of Smart City Digital Twins. The city's focus should be on creating a sustainable, connected, and forward-looking urban environment that enhances the quality of life for its residents.

Wrocław

The Wrocław workshop inputs highlights a range of solutions, visions, and near-future needs across various dimensions, such as Economy, Environment, Mobility, Governance, Living, and People (**Figure 39**). These insights on SCDT reflect the necessity of innovative approaches to address challenges and opportunities in Wrocław's development. Considering the workshop results, the integration of ICT in city services for sustainability, and community well-being is evident how SCDT project objectives are aligning with cities' needs against future uncertainties.

	CURRENT SOLUTIONS	NEAR FUTURE NEEDS	VISIONS
WROCLAW POLAND	• Emphasis on ambient technologies & smart lightning. • Mobility solutions, including sharing economy and autonomous cars. • Economic initiatives for revenue management and citizen benefits. • Governance improvements through electronic services.	• Expanding AR and VR usage. • Use of sensors and simulations for infrastructure. • Infrastructure funding models. • Collaborative efforts between universities and companies for technology innovation.	• A vision of a sharing economy and the role of infrastructure. • Autonomous vehicles and the impact on urban traffic. • Transition to digital, paperless bureaucracy. • The potential of the metaverse and AI in society.

Figure 39. *Key insights from the Wrocław workshop.*

Moreover, the workshops that were conducted in Wrocław have yielded significant insights into a range of areas related to urban development, namely in relation to the economy, environment, mobility, governance, living standards, and people. The purpose of these workshops was to gain an understanding of the current solutions, near-future needs, and visionary aspects of SCDT for various cities. Smart lighting, online platforms, green initiatives, support for small enterprises, autonomous vehicles, digitalization of government services, and health technology were just a few of the many issues they explored. Participants discussed on the potential and problems brought about by technological advancements, as well as the significance of financial incentives, the necessity for standardisation, and ethical issues. These observations will be crucial in determining how these cities develop in the future and how smart technologies are more widely adopted to enhance the resilience of smart cities in the future.

To further enrich these insights, firstly more insights for each dimension and each theme; Current Solutions, Visions and Near Future Needs, are needed. Additionally, it is vital to get more feedback and explore more in-depth for the following topics:

Cross-Dimensional Synergies: Are there opportunities for these dimensions to intersect and create integrated solutions? For instance, how can governance support environmental initiatives or mobility solutions enhance economic growth?

Community Engagement: How can residents and local communities actively participate in these initiatives and co-create solutions?

Technological Integration: What specific technologies (e.g., AI, IoT, blockchain) are expected to underpin these solutions, and how might they be seamlessly integrated?

Sustainability Metrics: What indicators or metrics are being considered to measure the sustainability and long-term impact of these solutions?

Collaboration and Funding: What collaboration mechanisms exist between public and private sectors, and what are the funding strategies in place or needed to realize these ideas?

Legal and Ethical Considerations: What legal and ethical issues have been identified, and how are they being addressed in the development of these projects?

By gaining more insights into these aspects, a holistic understanding of the current solutions, visions, and near-future needs in Wrocław could be achieved.

Vilnius

Important insights were obtained in Vilnius about many aspects of the development of SCDT (Figure 40) First, under the heading of "Current Solutions," Vilnius has projects pertaining to the environment, people, living aspects, economy, mobility, governance, and environment. These include supporting start-ups, centralized information systems, creative makerspaces, participatory budgeting, measuring air quality, improved mobility infrastructure, and technology developments in public services and governance.

	CURRENT SOLUTIONS	NEAR FUTURE NEEDS	VISIONS
VILNIUS LITHUANIA	• Growing bicycle roads and green city development. • Smart parking solutions. • Use of smart city lights. • Car sharing and sharing economy.	• Infrastructure needs for the sharing economy. • Mindset change regarding digital payments and paperless bureaucracy. • Ethical considerations for AI and data usage. • Standardized platforms and data. • Regulatory changes for AI and social media	• Focus on a green city and automated environmental monitoring. • A future with shared, autonomous transportation. • Transition to digital and avatar-based economic systems. • Predictive AI systems for optimizing city life.

Figure 40. *Key insights from the Vilnius workshop.*

Second, the "Visions" part outlines aspirational objectives for Vilnius in the areas of people, living, mobility, governance, and the environment. These include establishing one-stop shopping for services, utilizing virtual reality technology for a range of purposes, and establishing Vilnius as a centre for technology. Alongside cutting-edge transportation systems, improvements in digital governance, improved quality of life, and the incorporation of AI and robotics into daily life, environmental preservation and sustainability measures are also envisaged. Finally, the "Near Future Needs" highlight areas that still need improvement and attention. Although Vilnius has achieved great progress in several areas, there is still opportunity for improvement in the areas of the economy, environment, mobility, governance, quality of life, and people. These categories include, but are not limited to, supporting digital living solutions, enhancing waste management, and encouraging local companies. The most important lesson is that to achieve these goals for smart cities, funding from the European Union, meticulous planning, and innovative solutions are essential.

It is necessary to investigate economic sector activities, such as promoting local entrepreneurs, encouraging innovation, and establishing a business-friendly climate through public-private partnerships, to further progress Vilnius as a smart city. By enhancing waste management, growing green areas, adopting clean energy sources, and paying close attention to pollution and air quality, environmental sustainability can be increased. Vilnius should create an experiment lab for digital city education, deploy real-time sensor-equipped digital twins, and develop a complete smart city digital twin plan for infrastructure. Voting should use both technological and political methods to increase accessibility and transparency. Vilnius can advance digital twin solutions, enhancing inhabitants' quality of life via smart housing, healthcare, cultural initiatives, and safety measures. Vilnius is already skilled in several dimensions. Robotics and AI integration with the community can improve daily life even more for the locals. A "Think Big, Plan Carefully, and Fund with EU" strategy is considered as a requirement to achieve these aims to maximize the advantages of the European Union's help and acquire the resources that are required.

It is worthwhile to open a special parenthesis here and mention Vilnius's IMD Smart City Index 2023 analysis results (IMD Smart City Index, 2023, p. 169). IMD Smart City Index examines inhabitants' perceptions and expectations regarding smart city activities of the city in five major categories: health and safety, mobility, activities, opportunities, and governance. As a result of the Vilnius workshop, it was reported that the near future needs and vision insights of the participants were compatible with the 15 main issues prioritized by the expectations of those living in Vilnius and participated in IMD's survey work. This can be interpreted as Vilnius adopts an SCDT approach that also considers the expectations of the inhabitants.

Turku

At the Smart City Digital Twin (SCDT) workshop in Turku, Finland, current solutions, visions, and near future needs from a wide range of subject areas were uncovered (Figure 41). A strategic focus on economic growth, environmental sustainability, effective government, efficient mobility, and raising citizen quality of life characterizes the participants' approach to SCDT. Important takeaways from the session clarified ongoing projects, visions, and needs that have been recognized for the near future.

	CURRENT SOLUTIONS	NEAR FUTURE NEEDS	VISIONS
TURKU FINLAND	A strategic focus on economic growth, environmental sustainability, effective government, efficient mobility, and raising citizen quality of life characterizes the participants' approach to SCDT	• **Digital Twin Strategy and Research Funding:** Workshop insights emphasized the necessity for significant financing for research into both the fundamental and applied elements of digital twin technology • **Economic Strategies**: The workshop data highlights the importance of creating viable growth plans and business models in the context of digital twins • Necessity for **flexible legislation**, particularly in the context of autonomous mobility, and highlights **innovation clusters** as requiring specific mobility planning. • The necessity for a **trained workforce** in the creation of Smart City Digital Twins (SCDT)	• **Smart National API Strategy:** Because there is no standardized Smart National API approach, interoperability and smooth integration across diverse smart city efforts are difficult. • **Data Repository Management against Smart City Cyber Attacks:** The closure of some data repositories owing to national security concerns may cause disruptions in the operations of firms that rely on these repositories

Figure 41. *Key insights from the Turku workshop.*

Digital Twin Strategy and Research Funding: Workshop insights emphasized the necessity for significant financing for research into both the fundamental and applied elements of digital twin technology, as well as the significance of having a clear strategy in place for adopting digital twins in urban settings. This entails knowing the objectives, scope, and purpose of digital twin applications and making sure that ongoing project implementations have a strong basis for creative urban development in Turku.

Economic Strategies: The workshop data highlights the importance of creating viable growth plans and business models in the context of digital twins and recognizes the necessity for a larger budget allocation for pilot projects to evaluate digital twin concepts. There is a request for better knowledge of digital twin principles and their consequences for individuals and enterprises, as well as for increased communication and collaboration among local companies - possibly aided by the Chamber of Commerce and Business Turku.

Communication and Collaboration: Insights acknowledges the need for increased communication amongst regional businesses and recommends the construction of a platform or catalogue to help with SCDT innovations and Turku collaboration. Furthermore, a deeper comprehension of digital twin concepts is acknowledged to be necessary, considering their consequences for enterprises, local government, and individuals.

Environmental Sustainability: In the context of smart city and digital twin initiatives, participants expressed a need for an enhanced and faster planning process. The emphasis on building biodiversity highways, incorporating ecological and doughnut economy concepts, and calculating every individual's carbon footprint in Turku all point to an emphasis on environmentally responsible and sustainable urban development.

Mobility Challenges: The Turku workshop data recognizes the necessity for flexible legislation, particularly in the context of autonomous mobility, and highlights innovation clusters as requiring specific mobility planning. The importance of sustainable battery development was emphasized, with the focus on decreasing waste and enhancing car to shared mobility alternatives, and for urban areas to be planned properly.

Governance and Security: Insights highlighted the necessity of risk-taking pilot initiatives to test and deploy digital twin solutions, as well as involving multiple stakeholders and launching projects that foster innovation. There is a need for digital twin education in Turku, to raise awareness and knowledge among the general public and key stakeholders. It was proposed that the public sector, universities, and corporations work together more closely, focusing on common projects and collaborative activities on threats and uncertainties for resilient future of Turku in all six SC dimensions. Recognizing the sensitivity of GDPR questions and security concerns connected to open data, the development of a roadmap for smart governance to improve democracy and confidence in digital twin deployments was called for.

Living and Citizen Involvement: Participants also expressed a need for citizen initiatives connected to smart living, showing a participatory approach to urban development. The topic of whether a city is more vulnerable or resilient as a result of a digital twin was addressed, prompting analysis of potential hazards and advantages. Special input was made on on-line real-time voting mechanism in Turku.

People and Skills: The demand for unified and user-friendly digital services was stated, as was the necessity for integrated smart apps and information packages. The Helsinki's "My Data" concept was mentioned, which involves individuals having ownership over their personal data. The necessity for a trained workforce in the creation of Smart City Digital Twins (SCDT) was emphasized, suggesting a demand for personnel with the appropriate experience in this sector.

In addition to all these, some distinctive topics were brought up during the workshop discussions in Turku. Although some of them overlap with the workshop insights carried out in the partner cities, it is vital to evaluate them under separate headings as provided below.

Smart National API Strategy: Because there is no standardized Smart National API approach, interoperability and smooth integration across diverse smart city efforts are difficult. Creating a consistent framework for APIs across Finland is critical for encouraging collaboration and innovation among all other Finnish cities, including the City of Turku.

National Security and Data Repository Management against Smart City Cyber Attacks: The closure of some data repositories owing to national security concerns may cause disruptions in the operations of firms that rely on these repositories. This indicated that one firm in Turku crashed because of shutting open data. Striking a balance between protecting national interests and reducing the economic consequences for impacted business is a difficult task.

Smart Port City Concept in Turku: The Smart Port City idea offers integration issues in Turku, notably in integrating multiple technologies for effective port operations. However, the workshop's feedback was highly stimulating. Despite Turku Airport's more than 70-year existence, current global trends on Airport City (also known as Aerotropolis) concept development appear to have lost their importance in Turku. In this sense, balancing the optimization of port operations with airport operations may be significant to the growth of SCDT in Turku. However, environmental sustainability is still an issue, and there is a need for strong cybersecurity measures, community participation, and addressing any environmental effect and logistical issues related with these notions.

Overall, Turku's SCDT workshop was highlighted by a dedication to innovation, sustainability, and citizen centric SCDT development. A distinct digital twin approach, economic initiatives, and improved communication demonstrate the city's commitment to revolutionary urban planning. Prioritizing environmental sustainability, transportation problems, and governance considerations highlight Turku's complete approach even more. As the city navigates issues of citizen involvement, skill development, and national-level strategies, it has the potential to position itself at the forefront of smart city development, combining both bottom-up and top-down approaches promising positive effects on the economy, environment, and overall urban planning.

4.8. Futures Triangle Analysis: The Past, Present and the Future of SCDTs

Finally, we draw together our key insights from the four case cities into a futures triangle framework. Futures triangle is an analytical framework developed by a futurist Sohail Inayatullah (Inayatullah, 2008). It helps to position the phenomenon under analysis into the intersection of past, present and future, as the triangle consists of three dimensions: push of the present, pull of the future and weight of the past. Push of the present maps the current forces driving the development; pull of the future describes the visions and images of future; weight of the past describes barriers that are hindering development. Analysis of these three dimensions helps to assess the overall situation: is there enough push and pull factors driving the development forward or is the weight of the past too heavy slowing down the development. The three dimensions of the Futures Triangle Analysis can be summarized as follows (Modified, Sitra, 2023):

- Weight of the past: limitations, obstacles, commitments, worldviews, values, beliefs that prevent moving forward
- Push of the present: megatrends, trends, change processes that are driving the change in the present
- Pull of the future: Dreams, plans, visions that create images of future

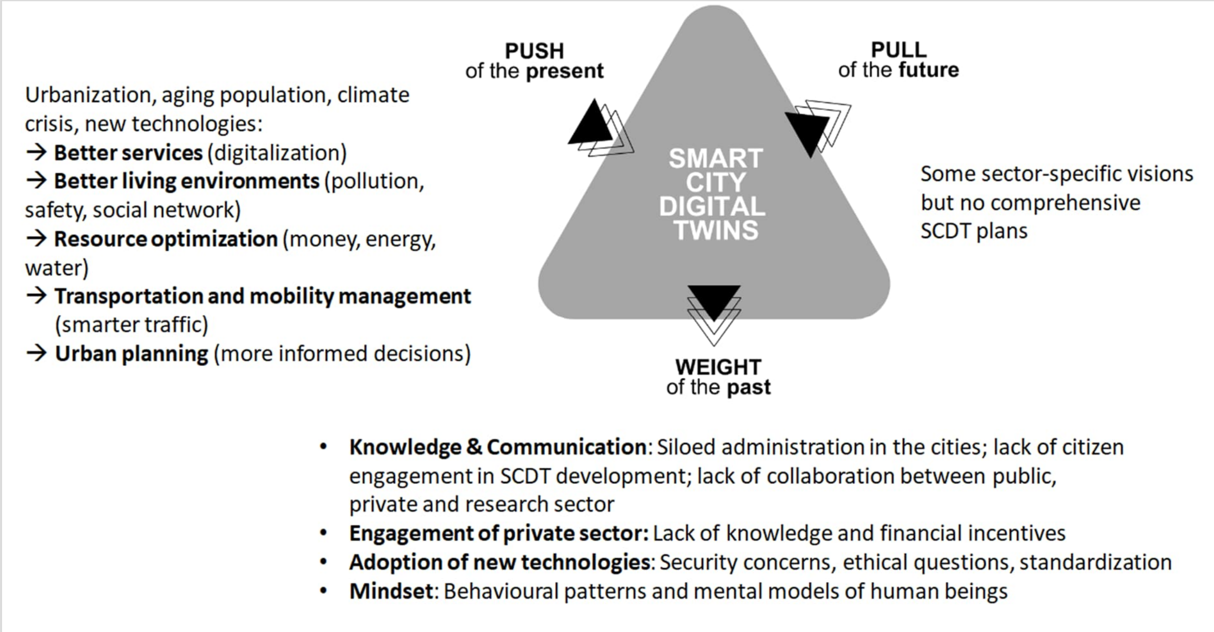


Figure 42. *Futures Triangle analysis of Smart City Digital Twin development in the case cities.*

As presented in the push and pull section of smart specialisation strategies (S3), analysis of push and pull factors should always be the starting point for regional strategies for smart specialisation (See Foray, 2023). By applying this push- and pull approach, we can also contribute to the smart specialisation strategy in the context of urban development. In this S3 approach way, the Futures Triangle analysis can be a sensible method choice for wider spatial planning.

In the present there exists several trends and processes that are driving the development of smart city digital twins. For example, climate crisis, urbanization, aging population, and new technology development can be categorized as key drivers of the SCDT development. These create demand for better, cost-effectively produced services. Particularly the need for more digitalization of services is high. Increasing number of urban populations calls for cities to become more pleasant living environments. For example, more efficient traffic and infrastructure management and processing of environmental pollution is needed. The escalating climate crisis calls for adaptive solutions in urban planning to tackle the changing environmental conditions, for example storm water management. All in all, the new technological development provides various opportunities to utilize the digital twin technology for resource and process optimization, more informed decision-making, better citizen services and environmental sustainability.

However, the past and present impose a great deal of weight on the smart city digital twin development. Many of these challenges are related to communication and knowledge sharing. One major burden is the fragmented nature of the SCDT development work. A lack of collaboration and communication platforms for bridging the public, private and research sector were reported. This hinders the development work, as innovation potential is wasted, and potential partnerships are not formulated. Moreover, inside the municipal organizations the administrative and development work related to smart city digital twins is siloed and the knowledge isn't shared across the siloes in the best possible manner. It was also reported that formulation of shared vision and motivation of decision makers was challenging. Moreover, it can be considered a hindrance that none of the cities reported engaging citizens actively to the SCDT development work. Following this, it was acknowledged that more knowledge on digital twins needs to be shared for citizens and private sector companies. Companies currently lack financial incentives to take part in the digital twin development, as more viable growth plans and business models would be needed.

Many of the challenges are also related to human behaviour. In the workshops, the topic of mental models and behavioural patterns of people were widely discussed. Particularly in Poland, the Soviet past was experienced to still outcast its shadow diminishing the willingness of people to adopt “smart solutions” that build on the idea of sharing economy. All in all, it was raised that a new kind of thinking is needed - starting from day care all the way to elderly care – in order to adopt “smart life” consisting of more resource wise living.

Finally, uncertainties related to security and ethics are leaving open questions for the future development of smart city digital twins. The recent global geopolitical development has raised new concerns related to the potential of cyber-attacks and weaponizing of digital twins against national security. For example, Vilnius has already closed some of its open data due to security reasons. Furthermore, the adoption of new technologies creating increasingly opportunities to surveillance of people’s behaviour raise ethical questions that need to be addressed before adoption.

To overcome the heavy weight of the past, strong pull of future visions for SCDT development would be needed. However, it seems that none of the case cities has yet formulated a comprehensive vision on utilizing digital twin technologies in smart city development. There exists some sector or technology specific plans and visions, for example how to utilize and develop smart traffic. But the big picture is missing.

5. CONCLUSIVE REMARKS AND REFLECTIONS

The development of SCDTs is hindered by the weight of the past, as is made clear by synthesising the policy and sectoral challenges with the Futures Triangle Analysis outlined in this report. For example, issues like digital twin development and short-termism are manifestations of deeply rooted organisational and institutional systems that hinder SCDTs advancement. The analysis demonstrates how past organisational barriers within city organisations limit collaboration and knowledge exchange, which sustains current impediments. This is exemplified by the fragmented social, ecological, and technical characteristics of SCDTs development. In addition, the absence of channels for cooperation and shared visions among stakeholders highlights the significance of past strategies that restrict future-oriented high-level approaches.

On the other hand, the pull of the future – embodied by the goals for the growth of SCDT – offers viable solutions to these problems. For example, the focus on socio-technical perspectives and citizen-centric digital twins in the creation of policies represents a forward-looking attitude that aims to solve present constraints and shape SCDTs future trajectories. Cities can start to move away from historical patterns of differentiated decision-making and bureaucratic weakness by conceiving of SCDTs as tools for boosting citizen engagement and addressing local contextual needs. Furthermore, the call for cooperation within the Quadruple Helix, or preferably Quintuple Helix (including environment for ecological aspects) which involve various stakeholders outside of the city governance and business participants, indicates an understanding of the necessity for novel holistic approaches to govern joint future visions that go beyond historical boundaries.

Nonetheless, the lack of inclusive visions that are especially suited to SCDTs development in the case cities draws attention to a lack of long-term planning and strategic vision. The pull of the future might not have the required strength to bring about significant change in the absence of bold and ambitious aspirations that go beyond immediate concerns and overcome historical obstacles. Therefore, while the pressure of the present offer chances and trends for the growth of SCDT, realising these opportunities requires overcoming the weight of the past and maximising the transformative potential found in future-focused strategies and visionary leadership.

It is also essential to trace the history of smart cities from their earlier iterations to their current state to contextualise the SCDTs development through the Futures Triangle Analysis results. Using technology to optimise and increase efficiency in urban infrastructure – such as traffic management and smart grids – was the main goal of smart city 1.0. However, this early stage frequently lacked comprehensive integration and public participation, reflecting a push towards the present fuelled by technical breakthroughs but constrained by the weight of earlier, isolated approaches to urban planning.

Smart City 2.0 included data-driven decision-making and participatory governance models, signalling a move towards citizen-centric approaches. During this phase, the future was pushed toward inclusivity and sustainability, with the goal of addressing the shortcomings of Smart City 1.0 while continuing to tackle historical obstacles to cooperation and creativity. Driven by cutting-edge technology like artificial intelligence and the Internet of Things, smart city 3.0 is an additional progression towards resilient and interconnected urban ecosystems. Incorporating social, economic, and environmental aspects into a common framework, this phase represents a more allencompassing vision for urban development. However, achieving the goals of Smart City 3.0 will necessitate overcoming deeply rooted bureaucratic systems, mental change and encouraging multi-stakeholder cooperation, highlighting the tension between past constraints and future possibilities in shaping urban futures. Only then, the integration of digital twins into smart city developments could be placed on a solid basis with articulated and inclusive approaches, and this paradigm shift might enable us to develop ***Smart City Digital Twins 1.0*** and its subsequent shifts on a foundational basis.

Boyd Cohen's SCW, which constitutes the analytical framework of our Foresight workshops, made the definition of the smart city concept more visually appealing by six smart city dimensions and feasible to assess insights of each city. It also revealed how the inputs put forward by the participants are interconnected, and that the developments of SCDTs need a joint vision, high-level approaches, and ontological methodologies. Although SCW includes ISO 37120 Sustainable Cities indicators in its 62 KPIs, since SCW was introduced, new ISO family have introduced, and ISO 30122 Smart Cities and ISO 37123 Resilient Cities indicators have demonstrated the necessity of future research avenues to improve the current SCW version.

Although the period of the project was short, the research team presents a more inclusive and updated SCW version below based on ISO *Sustainable development of communities – Relationship between the family of city indicators standards* in relation with the current solutions, near future needs and visions on SCDTs.

Figure 43. *Updated Smart City Wheel proposed by research team.*

Although the updated SCW presented here is still based on a simple analytical background, it can add an innovative approach to strategic foresight studies on SCDTs developments. Based on the preliminary thinking of current SCW, this version contains three main outlines. Core circle is used to analyse and determine the status of existing solutions of the cities with existing Boyd Cohen's SCW indicators within six smart city domains. Then, as a second step, with an external orientation, ISO 37122:2019 Sustainable Cities and Communities Indicators for Smart Cities are devoted to the Near Future Needs circle. It facilitates the analysis of near future needs. So that the outermost circle, namely Vision includes relevant ISO 37123:2019 Sustainable Cities and Communities Indicators Resilient Cities provide the desired and common future path with cross-analysis among three circles. Which indicators to include or which new domains to add to the six smart city domains should be tested and improved with empirical future research on SCDTs with more comprehensive applications.

This Smart City Digital Twins Project eBook reports in detail the main results of the SCDT mapping study. The project plan protocol was followed and implemented in planned stages of the project plan. Particularly challenging were the preparation of the workshop plans themselves and the recruitment and mobilisation of participants in the workshops themselves, as no specific financial incentives could be offered to the participants. Nevertheless, the SCDT foresight workshops were properly organised in Finland, Poland and Lithuania. This can be considered a success in the project. The discussions in the workshops were varied much and were useful. The final foresight workshop reporting took place because of comments received from participants. Responses were received to the evaluation and prioritisation forms, but not to all sections. The sections on digital twins' data and data management were proved to be particularly difficult and challenging.

The discussions in the workshops were varied and useful. The final reporting took place based on comments received from participants of workshops. Responses were received to the evaluation and prioritisation forms, but not to all critical survey sections. The sections on digital twins' data and data management were proved to be particularly difficult and challenging. There were shortcomings in demand-supply analyses of the availability of open data in target countries, in the assessment of data independence and in development plans and evaluation and formulation of data independence strategies. Reporting on key actors was also difficult to implement, because experts either did not want to provide more detailed information on these issues or they did not know enough about the issues in question. issues. The lesson to be learned from this is that data management in further projects must be given special attention – as well as the development of dynamic capabilities. Due to these shortcomings and data management challenges, dynamic capability development plans were difficult to develop. Therefore, during the project, the focus was on taking corrective knowledge management actions through separate publications. For these reasons, this report includes more extensive literature reviews and sections on modular data and information management, as well as a summary of best data management practices. It is good know that the project was carried out in a turbulent operating environment, and it is quite certain that the instability of the external operating environment (the war in Ukraine and the strengthening of the new Cold War atmosphere) contributed to the fact that there was little desire to open about data and information management issues among data management and city planning experts. Many cities have had to close previously open data sources and limit the openness of information and information systems. These data economy and data management problems and challenges were also highlighted in cooperation negotiations with Statistics Finland's experts in spring 2024 operated by PI Jari Kaivo-oja.

Huge efforts were made to compensate for this challenge and difficulties with our own high-quality conference publication, which was published during the project in a Springer publication series (see Appendix 3, Immonen et al., 2023). This can be considered a good data library and management report that supports Smart City Digital Twin activities in Finland. The report was distributed to foot experts during the project and will certainly be used in the planning of further SCDT projects. As this report explains, data governance is such a broad issue for cities that it requires additional active investment, and know-how's results can later be evaluated by assessing the reading interest received by the publications and the references to the publications themselves. In terms of impact, it is particularly important to focus on the City of Turku's smart city digital measures.

The results can later be evaluated by assessing the reading interest received by the publications and the references to the publications themselves. In terms of impact, it is particularly important to focus on the City of Turku's measures regarding the development of smart city digital twins.

During the project, big questions and challenges related to AI hype also emerged as a special challenge. This special challenge was met by publishing two scientific conference publications at ISPIM 2023 (See e.g., Kaivo-oja & Ainamo, 2023; Santonen & Kaivo-oja, 2023). One key conclusion in terms of content was that AI development is likely to accelerate the development of urban SCDT functions, and in this sense, the SCDT project was a timely project for broader urban development. During the project, positive signals were also received in connection with the organisation of the Smart City Expo conference in Barcelona, Spain, where Turku's own project contributions received quite wide international attention and concrete requests for cooperation in the development of smart city digital twins. International top experts and experts were also involved in the workshops organised in Turku, which can be considered a good success for the project. During the fact-finding visit to Japan, there was also extensive positive feedback on the SCDT project. The project clearly promoted a wider and active exchange of information also through the interest shown by a Business Finland expert in Tokyo, Japan.

Smart City Digital Twins (SCDTs) can efficiently manage long-term visions of cities through simulate alternative concepts and predictive analysis before they are implemented so as to identify possible challenges and long-term issues before they arise. This is a big advantage for smart city planning. Digital twins are advanced digitalised digital scenarios, which will radically change the nature of scenario planning and implementation in city planning and management. As reported in this e-Book report, smart city digital twin approach has a huge potential both socially and economically. To realise this great SCDT potential in practice, more determined coordination and integration are needed in smart cities. Coordination should focus especially on the development of data management in connection with the use of various digital twins. If this coordination and integration task will be neglected, this can become an obstacle to the rational and efficient use of digital twins in smart cities. In practice, responding to this challenge means that cooperation in the development of digital twins must be carried out across siloed organisational and professional boundaries.

To succeed in crossing organisational and institutional boundaries, city plans, and action programs should be developed to be more long-term and strategic. Development visions should also be shared and drawn up in cooperation, which in practice means participatory foresight and strategic dialogue between different stakeholders in connection with urban planning. Siloed approaches are a very problematic issue for wise and smart city digital planning. Therefore, siloed, and hierarchical processes should be consciously avoided in urban planning processes. Instead of puffy bureaucratic practices, agile co-design of citizens and different professionals in cities should be promoted systematically.

This study presents concrete case examples of how participatory foresight could work in cities. There are also international examples where the Smart City Wheel method was applied. This is a unique set of case studies, the results of which were reported in this e-book. A similar approach can be applied to other smart cities. We can suggest that benchmarking of smart cities is a very potential approach to smart city development. However, benchmarking comparisons alone is not enough in the field of smart city planning. We must proceed to comparative learning (bench-learning) and comparison activities generated through comparisons (bench-actions). We propose the use of benchmarking – bench-learning- bench-action – Approach (BM-BL-BA Approach), which is one promising possibility to collaborate in the fields of smart city planning field. This BM-BL-BA Approach can also be applied in various international and global arenas, also applying the Smart City Wheel approach, which can be linked to participatory foresight processes, as our case studies clearly show. In this way our case program in Gdańsk, Wrocław, Vilnius, and Turku is a unique case study example of organising smart city planning processes in a concrete city planning settings.

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APPENDIX 1. Mapping Survey Questions Grouped based on Futures Triangle Framework

Group 1. Facts about the current state of development

What kind of digital twin solutions and systems are currently used in your city? Please, name them and evaluate the pros and cons of each solution.

What service providers are used in your city? Please, name them and evaluate the pros and cons of each provider.

What kind of data repositories are used in your city? Please, name them and describe briefly what the data is about, who owns it and who uses it.

Who are the relevant stakeholders that work with smart city or digital twin development or related solutions in your city? For example, public organizations, companies, research institutes, and non-governmental organizations. Please, name the organizations.

Group 2: Push of the present

For what reasons and purposes is your city interested in developing digital twins?

What are the citizens' expectations for smart city and digital twin development? For example, has your city done an analysis of citizen needs?

What kind of smart city digital twin systems (platforms, apps, ecosystems etc.) is your city planning to develop in the near future? If there exists new research or initiatives etc. related to smart cities or digital twins in your city, could you please provide links.

What kind of technological trends or emerging technologies are you currently following? How do you expect these trends to impact smart city digital twin development in your city?

Group 3: Pull of the future

What kind of digital visions or strategies do you have on national and local level that steer the development of digital twins in the city context?

Group 4: Weight of the past

What are the main challenges you have encountered in the smart city digital twin development? How do you plan to solve them?

APPENDIX 2. Boyd Cohen Smart City Wheel KPIs[6]

Dimension	Working Area	Indicator	Description
Environment	Smart Buildings	Sustainability-certified Buildings	Number of LEED or BREAM sustainability certified buildings in the city (Note: if your city uses another standard please indicate)
			% of commercial and industrial buildings with smart meters
			% of commercial buildings with a building automation system
		Smart homes	% of homes (multi-family & single-family) w/ smart meters
	Resources Management	Energy	% of total energy derived from renewable sources (ISO 37120: 7.4)
			Total residential energy use per capita (in kWh/yr) (ISO 37120: 7.1)
			% of municipal grid meeting all of following requirements for smart grid (1. 2-way communication; 2.) Automated control systems for addressing system outages 3.) real-time information for customers; 4.) Permits distributed generation; 5.) Supports net metering
		Carbon Footprint	Greenhouse gas emissioned measured in tonnes per capita (ISO 37120: 8.3)
		Air qualty	Fine Particular matter 2.5 concentration (µg/m3) (ISO 37120: 8.1)
		Waste Generation	% of city's solid waste that is recycled (ISO 37120: 16.2)
			Total collected municipal solid waste city per capita (in kg) (ISO 37120: 16.3)
		Water consumption	% of commercial buildings with smart water meters
			Total water consumption per capita (litres/day) (ISO 37120: 21.5)
	Sustainable Urban Planning	Climate resilience planning	Does your city have a public climate resilience strategy/plan in place? (Y/N) If yes provide link.
		Density	Population weighted density (average densities of the separate census tracts that make up a metro)
		Green Space per capita	Green areas per 100,000 (in m2) (ISO 37120: 19.1)
Mobility	Efficient Transport	Clean-energy Transport	Kilometers of bicycle paths and lanes per 100,000 (ISO 37120: 18.7)
			# of shared bicycles per capita
			# of shared vehicles per capita
			# of EV charging stations within the city
	Multi-modal Access	Public Transport	Annual # of public transport trips per capita (ISO 37120: 18.3)
			% non-motorized transport trips of total transport
			Integrated fare system for public transport
	Technology Infrastructure	Smart cards	% of total revenue from public transit obtained via unified smart card systems
		Access to real-time informatio	Presence of demand-based pricing (e.g. congestion pricing, variably priced toll lanes, variably priced parking spaces). Y/N
			% of traffic lights connected to real-time traffic management system
			# of public transit services that offer real time information to the public: 1 point for each transit category up to 5 total points (bus, regional train, metro, rapid transit system (e.g. BRT, tram), and sharing modes (e.g. bikesharing, carsharing)
			Availability of multi-modal transit app with at least 3 services integrated (Y/N)
Government	Online services	Online Procedures	% of government services that can be accessed by citizens via web or mobile phone
		Electronic Benefits Payments	Existence of electronic benefit payments (e.g. social security) to citizens (Y/N)
	Infrastructure	WiFi Coverage	Number of WiFi hotspots per km2
		Broadband coverage	% of commercial and residential users with internet download speeds of at least 2 Mbit/s
			% of commercial and residential users with internet download speeds of at least 1 gigabit/s
		Sensor Coverage	# of infrastructure components with installed sensors 1 point for each: traffic, public transit demand, parking, air quality, waste, H2O, public lighting
		Integrated health + safety operations	# of services integrated in a singular operations center leveraing real-time data. 1 point for each: ambulance, emergency/disaster response, fire, police, weather, transit, air quality
	Open Government	Open Data	Open data use
		Open Apps	# of mobile apps available (iPhone) based on open data
		Privacy	Existence of official citywide privacy policy to protect confidential citizen data
Economy	Entrepreneurship & Innovation	New startups	Number of new opportunity-based startups/year
		R + D	% GDP invested in R&D in private sector
		Employment levels	% of persons in full-time employment (ISO 37120: 5.4)
		Innovation	Innovation cities index
	Productivity	GRP per capita	Gross Regional Product per capita (in US$, except in EU, in Euros)
	Local and Global Conexion	Exports	% of GRP based on technology exports
		International Events Hold	Number of international congresses and fairs atendees.
People	Inclusion	Internet-connected Household	% of Internet-connected households
		Smart phone penetration	% of residents with smartphone access
		Civic engagement	# of civic engagement activities offered by the muncipality last year
			Voter participation in last municipal election (% of eligible voters) (ISO 37120: 11.1)
	Education	Secondary Education	% of students completing secondary education (ISO 37120: 6.3)
		University Graduates	Number of higher education degrees per 100,000 inhabitants (ISO 37120: 6.7)
	Creativity	Foreign-born immigrants	% of population born in a foreign country
		Urban Living Lab	# of officially registered ENOLL living labs
		Creative Industry Jobs	Percentage of labor force (LF) engaged in creative industries
Living	Culture and Well-being	Life Conditions	Percentage of inhabitants with housing deficiency in any of the following 5 aereas (potable water, sanitation, overcrowding, deficient material quality, or lacking electricity)
		Gini Index	Gini coefficient of inequality
		Quality of life ranking	Mercer ranking in most recent quality of life survey
		Investment in Culture	% of municipal budget allocated to culture
	Safety	Crime	Violent crime rate per 100,000 population (ISO 37120: 14.5)
		Smart Crime Prevention	# technologies in use to assist with crime prevention, 1 point for each of the following: livestreaming video cameras, taxi apps, predictive crime software technologies
	Health	Single health history	% of residents w/ single, unified health histories facilitating patient and health provider access to complete medical records
		Life Expectancy	Average life expectancy (ISO 37120: 12.1)

[6]Source : https://www.smartcitiescouncil.com/sites/default/files/public_resources/Smart%20City%20Index%20Master%20Indicators_0.xlsx

APPENDIX 3. Modular Smart City Digital Twins: A Survey of Key Technologies

Modular Smart City Digital Twins: A Survey of Key Technologies ⋆

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Abstract. Smart City Digital Twins (SCDT) are virtual replicas of cities (or parts thereof) that integrate real-time data from various sources to enable simulation, monitoring, and optimization of urban systems for more efficient and sustainable urban management. In this article, we provide a survey of modular SCDTs, covering standardization and key enabling technologies. Modular hardware and software architectures pave way for standardization, which is crucial for efficient maintenance as well as scalability and portability to new application domains.

1 Introduction

For the past decades, cities worldwide have been adopting novel information technology solutions to address growth-induced complexities, human well-being and global sustainability issues. Cities are essentially transforming into *Smart Cities* that prioritize enhanced efficiency, improved sustainability, and increased quality of life for residents [27]. In the context of smart cities, *Digital Twins* — computer replications of physical devices, systems or processes connected both ways to the physical domain in real time — are a key enabling technology [16].

Modular hardware and software architectures pave way for standardization. For Smart City Digital Twins (SCDT), standardization allows for flexibility and scalability, making it easier to modify, update, and maintain the systems. This is important for addressing urban growth and other changes in the city environment as well as portability of the technological solutions to new application domains. In the recent extensive survey of digital twin supported smart cities [46], Wang et al. found unstructuredness, heterogeneity and asynchronity of data as well as lack of system interoperability the key research challenges for SCDTs. Further, they concluded that standardization (of data and interfaces) is expected to be a key future development that addresses these challenges. The purpose of the present article is to provide a survey of modular SCDTs, covering standardization and key enabling technologies.

Our focus is on modular software and hardware solutions, which typically specify *how* data is stored or transmitted but do not address the *content* of that data. The content arises from knowledge management across SCDT applications (and even domains), typically based on models for *information*, e.g. Building Information Model (BIM), and *representations* of that information, e.g. Extensible Markup Language (XML). In some approaches these are not separated, e.g. BIMXML [18]. However, at present, such standardization of content only appears to be at its infancy, being very application-specific [33]. For instance, while BIM covers building information, there seems to be no standardized information model that also covers human comfort for the same building (though that is an active area of research, see e.g. [26]).

2 Smart City Digital Twins

SCDTs have been widely studied in the academic literature in the past few decades. In this section, we briefly describe their history, list some practical applications, and describe the technology context. For more information on SCDTs, we refer the reader to the other recent surveys [46, 50], and especially the book [10] edited by Farsi et al.

2.1 Historical development

The roots of smart cities are in the 1980s, with limited technological integration and an emerging focus on improving urban infrastructure through basic automation and computerization [8]. During the 1990s, smart cities began to explore broader applications of technology, with increased emphasis on digital connectivity, information sharing, and the integration of information and communication technology (ICT) into urban governance and

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service delivery [19]. In the early 2000s, through emergence of cloud computing, smart cities ramped up technology and data-driven decision-making, such as intelligent transportation systems, energy efficiency initiatives, and digital governance platforms [29]. Recently, in the 2010s and 2020s, smart cities have witnessed significant technological advancements compared to the early 2000s, especially in proliferation of Internet of Things (IoT) devices, improved data connectivity, advanced data analytics, and utilization of artificial intelligence (AI). The apex of this development is modern AI-driven decision-making to enhance sustainability, mobility, and quality of life in cities [4]. The technologies of modern smart cities are essentially those utilized in digital twins, which serve as virtual replicas of physical assets or systems, enabling real-time simulation and analysis for efficient monitoring and management. This motivates the SCDT terminology.

2.2 Applications

SCDTs have a wide range of applications that contribute to urban development, sustainability and system efficiency. Among the many applications that aim for optimized resource usage use we mention real-time monitoring and optimization of energy consumption in buildings [37], intelligent traffic management systems for efficient transportation [22], dynamic waste management systems for optimizing collection routes and reducing environmental impact [49], predictive maintenance of infrastructure assets to minimize downtime and enhance reliability [15], smart grid management to balance energy supply and demand [6], integrated water management systems for efficient water distribution [34] and wastewater treatment [43].

Besides these, perhaps more technology-oriented solutions, there are also SCDT applications that more specifically target citizen engagement and participatory decision-making [24, 48], as well as human safety in disaster management [13] and health [17]. SCDT-based optimization of manual work processes, besides efficiency, also with respect to equality and human well being have received attention in the literature [21, 20]. Across these applications, the key contribution of SCDTs is their ability to provide, and even synthesize, timely information for decision-making.

2.3 Technology context

Figure 1 describes the typical technology interconnections witnessed in SCDT applications, with the focus of the present article (*Interoperability and standards*) highlighted. The system or process is at the top of the diagram, whereas its human user is at the bottom. The magenta boxes consist mostly of physical hardware, whereas the blue boxes are mostly software systems. For systemic resiliency, cybersecurity should be addressed in parallel with all other SCDT technologies [12].

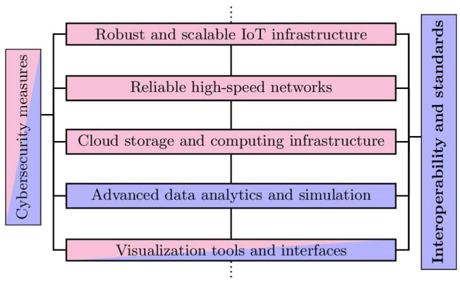

Fig. 1: Arrangement of SCDT technologies (red: hardware, blue: software)

In Figure 1, *robust and scalable IoT infrastructure* refers to a reliable and flexible network of interconnected devices and sensors that can handle large volumes of data. This is crucial for SCDTs as it enables the comprehensive monitoring and analysis of urban systems in real-time, when combined with *reliable high-speed communication networks* (often wireless). *Cloud storage and computing infrastructure* refers to a centralized and scalable hardware platform that allows for efficient storage, processing, and analysis of vast amounts of data generated by SCDTs, enabling enhanced computational power, data accessibility, and collaborative capabilities to support effective decision-making and optimization of urban operations. *Advanced data analytics and simulation* utilize the computing resources — nowadays massively parallel computing for near real-time response time — in sophisticated applications, algorithms and models to derive insights, patterns, and predictions from the monitoring data collected, enabling evidence-based decision-making, predictive capabilities, and optimization of urban systems and services. Finally, *visualization tools and interfaces*, including traditional human-machine interfaces (HMIs) and emerging concepts like the Metaverse [28], enable stakeholders to interact with and navigate the digital twin environment, fostering collaboration, and facilitating the exploration of diverse scenarios and data insights for informed decision-making.

3 Interoperability and standards: Modular solutions

Within the SCDT technology context of Subsection 2.3, we now focus deeper on interoperability and standards. We begin by listing the benefits of modularization and standards in Subsection 3.1, then introduce a hierarchy for the present survey in Subsection 3.2 and tabulate the features, advantages and disadvantages of different components. Finally, Subsection 4 contains the conclusions of this review.

3.1 Why modularize SCDTs?

The benefits of modular software architecture and standardization for SCDTs are listed below.

1. **Flexibility and scalability**: Modular software architecture allows SCDTs to easily adapt and handle increasing data volumes.
2. **Rapid development and maintenance:** The modular approach enables quick development and maintenance of system components.
3. **Interoperability and compatibility:** Standardization promotes seamless integration between different software systems, facilitating collaboration and exchange of data and functionalities in SCDTs.
4. **Reduced complexity:** Standardization facilitates plug-and-play type system integration, thus reducing complexity.
5. **Enhanced collaboration:** Standardization facilitates easier collaboration among different stakeholders involved in SCDTs, promoting effective teamwork and knowledge exchange.

3.2 Hierarchy

Figure 2 proposes a hierarchy for items in SCDT *Interoperability and standards*, according to which the remainder of this survey is organized. The items in the hierarchy are described below.

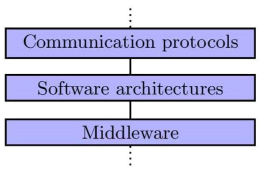

Fig. 2: Hierarchy of Interoperability and standards for SCDTs.

Communication protocols Communication protocols in SCDTs are standardized sets of rules and procedures for data transfer between system components (sensors, storage systems, models, etc). They enable connectivity and interoperability between physical world measurements and software systems. Among a few others, the following communication protocols are used in typical SCDT implementations: **MQTT** (Message Queuing Telemetry Transport) [32, 2], **CoAP** (Constrained Application Protocol) [38], **LWM2M** (Lightweight Machine-to-Machine) [40], **DDS** (Data Distribution Service) [42, 2], **AMQP** (Advanced Message Queuing Protocol) [45], and **WebSockets** [47]. Their features are described in more detail in Table 1.

Among these, MQTT, in particular, has gained significant popularity and adoption in IoT and smart city contexts due to its lightweight nature and efficient publish-subscribe messaging paradigm. We emphasize that these communication protocols can facilitate data transfer both from the sensors to the analytics (or simulation) model and from that model to the end users.

Software architectures In this article, standardized software architectures refer to the high-level design structures that govern the organization, integration, and behavior of software components in SCDTs. While a protocol (discussed above) defines rules for communication and data exchange, software architecture defines the overall structure and design of a software system. Among others, the following software architectures are used in typical SCDT implementations: **Microservices** [35], **Event-driven** [51], **Edge computing** [9], **Hybrid cloud** [3] and **Data lake** [11]. The features and differences between these architectures are elaborated in Table 2.

Table 1: Comparison of communication protocols for SCDTs.

Protocol	Features	Advantages	Disadvantages
MQTT (Message Queuing Telemetry Transport)	Publish-subscribe model for real-time data communication over TCP. Lightweight design.	Real-time communication, scalability, efficient data distribution in centralized applications.	Overheads may affect large-scale/high-frequency applications, only 3 levels of Quality-of-Service (QoS).
CoAP (Constrained Application Protocol)	Request-response model for resource-constrained devices. Focus on efficiency for limited processing power and bandwidth.	Fast UDP communication, lightweight, resource-constrained devices support.	Limited adoption and support in existing middleware, reliability of UDP (vs. TCP), potential issues in handling large data payloads.
LWM2M (Lightweight Machine-to-Machine)	Device management capabilities, standardized registration, monitoring, firmware updates.	Standardization of IoT device management.	Learning curve, built on top of CoAP (see its disadvantages above)
DDS (Data Distribution Service)	Real-time peer-to-peer data exchange, encryption.	Efficient communication in distributed (decentralized) applications, control over QoS.	Complexity, overheads, best suited for large-scale applications
WebSockets	Persistent full-duplex point-to-point communication over TCP. Real-time updates for user interfaces.	Real-time interactions, user interface updates, support for large messages.	Best suited for real-time dashboards and user interactions, requires a persistent connection (resources).

Table 2: Comparison of software architectures for SCDTs.

Architecture	Features	Advantages	Disadvantages
Microservices Architecture	Decomposes application into small, deployable services.	Enhances agility, scalability, and ease of maintenance by separate technology stacks.	Requires careful management of inter-service communication and potential performance overhead.
Event-Driven Architecture	Enables asynchronous communication, real-time responses, and component decoupling through events.	Supports real-time interactions, scalability, and flexibility in system components.	Complex event handling, potential increased system complexity, and learning curve for event-driven programming.
Edge Computing Architecture	Processes data at the network edge, reducing latency and enabling real-time decision-making.	Low latency, reduced data transmission, improved responsiveness.	Limited processing power, potential security challenges at the edge, requires managing distributed resources.
Hybrid Cloud Architecture	Combines on-premises and cloud resources for flexibility in optimization.	Scalability, cost-efficiency, data residency compliance.	Requires integration between on-premises and cloud systems, potential data synchronization challenges.
Data Lake Architecture	Provides a centralized repository for storing and analyzing large volumes of raw data.	Supports data-intensive applications, data exploration, and analytics.	Data governance challenges, potential data silos, requires proper data management strategies.

Middleware Middleware refers to software that acts as a bridge between an operating system, database and/or applications. In the context of SCDT interoperability and standards, it is typically implemented according to one of the above key software architectures and protocols. Although commercial middleware solutions exist, in this survey, we only focus on open-source solutions.

At the heart of modular SCDTs middleware is the concept of co-simulation, which refers to distributed co-execution of independent subsystem simulation models in order to represent a large, coupled or otherwise complex physical system. Standardization of co-simulation facilitates wrapping digital twin implementations (simulation models or equivalent) into modules with standardized mechanisms for data input/output and parameterization [1]. There are a number of domain-specific co-simulation standards, such as the Open Simulation Interface (OSI) for virtual automated driving [25] and Open Simulation Platform (OSP) for maritime applications [30]. However, to the authors' knowledge none exist specifically for SCDTs.

A precursor for standardized co-simulation is standardized packaging of different simulation models (and the associated inputs and outputs) implemented in different modeling software. The most widely used standard is the Functional Mockup Interface (FMI), which defines a zip-file container for the description, exchange and storage of simulation artefacts [5]. The following open-source co-simulation systems support the FMI standard: **MCX** (ModelConductor eXtend) [1, 39], **OMSimulator** (OpenModelica Simulator) [14] and **DCP** (Distributed Co-simulation Protocol) [23]. These solutions are compared in Table 3. Among them, MCX is arguably the simplest and most lightweight solution whereas DCP and OMSimulator are more extensively developed and tested but also more elaborate to take into use.

Besides the *co-simulation* middleware solutions discussed above, there are also *generic* middleware solutions that are widely used especially in IoT applications. Supplementing the recent survey of Toutsop et al. [44], in Table 4, we give a brief comparison of the following open-source middleware: **Eclipse OM2M** (One Machine-To-Machine) [41], **FIWARE** [7] and **ThingsBoard** [36]. Note that besides OM2M, the Eclipse Foundation also hosts the Eclipse IoT "top-level project" that aims to provide a collaborative and open-source community for building IoT solutions [31].

Table 3: Comparison of open-source co-simulation middleware solutions for SCDTs.

Solution	Features	Advantages	Disadvantages
ModelConductor eXtend	FMI support, real-time data collection, asynchronous processing, queues	Multi-fidelity simulation models as digital twins, asynchronous data streams	Only tested for traditional engineering applications
OMSimulator	Support for Modelica language, FMI support, ordinary and delayed (transmission line) connections	Versatile model library (OpenModelica) also supporting numerical optimization, active user community	Learning curve, system integration challenging (or expensive)
DCP	Discrete-state machine, real-time and non-real-time operation	Parallel and distributed computing, large-scale simulations	Lack of widespread compatible simulation software

Table 4: Comparison of generic open-source middleware solutions for SCDTs.

Solution	Features	Advantages	Disadvantages
Eclipse OM2M	Device connectivity, data exchange, event processing, support for oneM2M standard	Modular and standardized, real-time interaction with physical systems	Steep learning curve for beginners
FIWARE	Standardized APIs, FIWARE Context Broker, NGSI APIs	Extensive ecosystem, modular and scalable, real-time data management	Requires additional configuration for specific use cases
ThingsBoard	Device management, data collection, real-time visualization	User-friendly interface, rule-based event processing, real-time connectivity	Limited scalability for large-scale deployments

4 Conclusions

In this article, we have provided a survey of modular Smart City Digital Twins, covering standardization and key enabling technologies. Among its benefits, described in this article, standardization allows for flexibility and scalability, making it easier to modify, update, and maintain the digital twin information systems.

This article proposes to address modularity and standardization in three connected layers: Communication protocols, software architectures and middleware solutions. For middleware, further separation is made into co-simulation platforms (which pertain to real-time simulation models) and generic open-source middleware (which pertain to visualization, among others). Several features of the key technologies were tabulated and respective advantages and disadvantages, from SCDT points of view, were described.

The many applications referenced in this article demonstrate the substantial benefits and growth potential of Smart City Digital Twins worldwide. Standardization is key to managing this growth. However, further work is needed especially in standardization of data content, which today still tends to be at its infancy, being very domain-specific (such as BIM). Standardization of data is not addressed in the present survey.

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APPENDIX 4. Knowledge Management Links of Smart City Digital Twins

Smart City Themes

Smart City Institute Japan
https://www.sci-japan.or.jp/english/index.html

Nordic Smart City Network
https://nscn.eu/

Nordic Urban Living Labs Projects
https://nscn.eu/Citylabs

FinEst Centre for Smart Cities
https://finestcentre.eu/

European Data Space for Smart Communities
https://www.ds4sscc.eu/

Smart City Observatory
https://www.imd.org/smart-city-observatory/home/

City Comparison
https://www.imd.org/smart-city-observatory/home/city-comparison/

IESE Cities in Motion Index
https://www.iese.edu/insight/

Urban Mobility Readiness Index
https://www.oliverwymanforum.com/mobility/urban-mobility-readiness-index.html

Digital Twin Themes

Centre for Digital Built Britain. Centre for Digital Built Britain completed its five-year mission and closed its doors at the end of September 2022. This website remains as a legacy of the achievements of our five-year foundational journey towards a digital built Britain.
https://www.cdbb.cam.ac.uk/subject/digital-twins

Swedish Digital Twin Consortium, SDTC
https://www.sdtc.se/

How digital twins can make smart cities better? Real-time simulations can create a bridge between physical and virtual worlds
https://www.pwc.com/m1/en/publications/documents/how-digital-twins-can-make-smart-cities-better.pdf

McKinsey Report: Digital twins: The foundation of the enterprise metaverse
https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/digital-twins-the-foundation-of-the-enterprise-metaverse

Digital Twin Consortium
https://www.digitaltwinconsortium.org/

Discover 5 Top Digital Twin Startups Impacting Industry 4.0. StartUs Insights
https://www.startus-insights.com/innovators-guide/5-top-emerging-digital-twin-startups-impacting-industry-4-0/

Smart Specialisation Strategy

S3 Platform
https://s3platform.jrc.ec.europa.eu/

S3 Tools and Data Sources
https://s3platform.jrc.ec.europa.eu/tools

Innovation for place-based transformations ACTION book
https://s3platform.jrc.ec.europa.eu/actionbook

European Digital Innovations Hubs

European Innovation Hubs Networks

https://european-digital-innovation-hubs.ec.europa.eu/home

The 4 European EDIHs selected from Finland:

1. EDIH Robocoast, with Prizztech OY, (manufacturing industry, Web: https://robocoast.eu/),
2. EDIH HealthHub Finland, with Turku Science Park Oy as coordinator (health), Web: https://healthhubfinland.eu/
3. EDIH Finnish AI Region, FAIR with the City of Helsinki as coordinator (digital ser-vices, smart cities and health), Web: https://www.fairedih.fi/
4. EDIH Location Innovation Hub, with National Land Survey of Finland as coordinator (geographic information), Web: https://locationinnovationhub.eu/fi/

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