UNIVERSITY OF TURKU
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Innovation Policy Roadmapping for the Future Finnish Smart City Digital Twins

Towards Finland National Digital Twin Programme

Futures Studies/Turku School of Economics
Master's thesis

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Dator's second law of the future…

"Any useful idea about the futures should appear to be ridiculous."

(Dator 2019, 4)

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Abstract

Smart City Digital Twins (SCDTs) emerge as a transforming concept with the ability to redefine the future of cities in the fast-paced evolving landscape of urban development. This qualitative futures research explores thoroughly into the complex interaction of socio-technical dynamics in the Finnish setting, investigating the several ways SCDTs might revolutionise urban spaces and create resilience. By utilizing Innovation Policy Roadmapping (IPRM) method for the first time on SCDTs, it reveals the diverse capacities of SCDTs across domains such as urban planning, scenario developing, What-IF analysis, and public involvement through a rigorous examination of academic literature and multi-level analysis of expert interviews. The research emphasises the critical role of policymakers and sectoral actors in building an environment that allows Finnish SCDTs to survive in the face of technological improvements. Furthermore, it emphasises the convergence of SCDTs and Futures Studies approaches, giving a visionary path to adaptable and forward-thinking urban futures. The contributions of this study extend beyond the scope of Finnish SCDTs, giving inspiration for sustainable smart city transformations, potential foundational insights towards Finland National Digital Twin Programme and paving the way for the incorporation of futures studies methodologies and digital twins to mitigate uncertainties and create resilient urban futures. Longitudinal impact assessments, real-time citizen-centric foresight applications via SCDT, and the investigation of SCDTs' role in disaster mitigation and social well-being are among the identified future research directions, providing a comprehensive roadmap for leveraging SCDTs as transformative tools for building sustainable urban futures.

Key words: Smart City Digital Twins, Futures Studies, socio-technical transformation, innovation policy roadmapping

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LIST OF COMMON ABBREVIATIONS

3D – Three-Dimensional
AI – Artificial intelligence
AR – Augmented Reality
BIM – Building Information Modelling
CIM – City Information Modelling
CPS – Cyber-Physical System
DT – Digital Twin
GIS – Geographic Information Systems
GPS – Global Positioning System
ICT – Internet and Communication Technologies
IoT – Internet of Things
IPRM – Innovation Policy Roadmapping
IT – Information Technology
ML – Machine Learning
MLP – Multi-level Perspective
SC – Smart City
SCDT – Smart City Digital Twin
VR – Virtual Reality
XR – Extended Reality

1 Introduction

1.1 Introduction to Topic

This qualitative futures research delves deeply into the intricate socio-technical transformation of SCDTs within the unique context of Finland, revealing their enormous potential to catalyse a paradigm shift in Finnish urban settings and cultivate resilience in the face of modern urban challenges. Smart City Digital Twins (SCDTs) are a novel concept that promises to redefine the fundamental perspectives on smart cities in today's dynamic urban development setting. As cities become more complex and connected, the implementation of SCDTs provides an innovative prism through which urban planning, infrastructure management, and public involvement may be reinterpreted and transformed.

This study was built on a thorough and meticulous analysis of the academic environment, emphasising the multiple capabilities and transformational influence of SCDTs across a wide range of aspects. This study provides a comprehensive and holistic understanding of the intricate forward-looking policy dynamics, enabling technologies, and collaborative strategies that underpin the full realisation of SCDTs' transformative potential, based on a synthesis of diverse research investigations, reflecting expert's insights' multi-level analysis, and the ground-breaking Innovation Policy Roadmapping (IPRM) approach. With a strong emphasis on expert perspectives, this study reveals a rich milieu of advantages that SCDTs bring to the forefront, ranging from informed and data-driven decision-making, scenarios, and What-IF analysis to optimised resource allocation and better citizen well-being.

Furthermore, the investigation goes further to highlight the critical importance of the Innovation Policy Roadmapping (IPRM) method of futures research. The IPRM technique, which serves as a systematic and organised framework, unfolds the complex interplay of socio-technical system and regime, their policies, new technologies, and shared vision within the dynamic setting of SCDTs. This research draws useful insights into the problems and potential buried within the integration and utilisation of SCDTs within the lively and changing environment of Finnish cities by interviewing specialists. The IPRM process contains a rich mine of actor-oriented policies, transformative technology enablers, and forward-thinking strategies that are critical in paving the way for the transformational journey towards the realisation of the Finland Digital Twin Programme.

Policymakers and sectoral actors have a critical role in building an environment that fosters innovation in the face of fast technological progress. To meet the ever-changing challenges, they pioneer incentive programmes, enable talent building, and champion novel procurement processes. The importance of collaborative efforts across multiple stakeholders, adherence to standardised data practises, and the ethical and responsible creation and use of technology—including the integration of AI, ML, IoT and effective data governance—comes to the forefront as the study progresses.

The fusion of SCDTs with the visionary lens of Futures Studies methodology emerges as a captivating narrative. The path for the integration of SCDTs and their transformational synergy with Futures Studies approaches takes centre stage, ushering in a new way to design resilient futures. In today's digital age cities are grappling with the difficulties of urbanisation, technological disruptions, and changing socio-technical environments. Accordingly, the convergence of Smart City Digital Twins and foresight methods reveals a unique way towards versatile urban futures. As this exploratory futures research concludes, it opens the door to an array of untapped possibilities, inviting mankind to embrace the revolutionary capabilities of SCDTs and begin on a path towards adaptive but also visionary urban futures.

1.2 Research Questions and Objective

This study revolves around two research questions - RQs:

> RQ1. "What kind of future-oriented innovation policies are needed for the future of Finnish smart city digital twins by 2035?
>
> RQ2. "How can Smart City Digital Twins be applied as testbeds for Futures Studies tools?

The aim of this research was to anticipate the future of Finnish Smart City Digital Twins - SCDTs and develop Innovation Policy Roadmapping for resilient socio-technical city transitions against future uncertainties. The study was directed by two specific objectives, namely:

> By "RQ1", to analyse current SCDTs understanding and explore future-oriented innovation policies that can facilitate the systemic transformation of

Finnish SCDTs by 2035, focusing on developing an innovation policy roadmapping (IPRM) approach to address the complexity of socio-technical system transformations within Finnish cities.

By “RQ2”, to explore and evaluate the potential functions of Futures Studies tools within the context of SCDT applications, investigating how the successful integration and utilization of Digital Twins in future smart cities can be enhanced and stretched by the capabilities of Futures Studies methods and tools.

1.3 Scope of the Research

This study's focus was on exploring prospective policy innovations and the possible use of futures studies tools in SCDTs in the context of Finnish cities by 2035. The purpose of the study was to assess status of SC and Digital Twin – DT developments and anticipate the elaboration of Finnish SCDTs and generate an Innovation Policy Roadmapping (IPRM) that can guide a resilient SC socio-technical transformations in the face of impending uncertainties.

To fulfil the study's goals; the research investigated and examined the forward-looking policy design changes required for the systemic transformation of Finnish smart cities. It comprehends the difficulties brought on by socio-technical transitions with the goal of creating an IPRM specifically for Finnish smart cities. To handle the potentials and difficulties of upcoming SCDT advances, the scope includes studying many policy areas such as urban planning, governance, sustainability, technological integration, and public involvement. Moreover, by gathering insights from interview participants, this study also examined the possibility of the methods and tools used in future studies within the context of DTs for smart cities.

Overall goal by addressing these research questions and objectives was to offer forward-looking policy suggestions for policymakers, sectoral players, city planners, and stakeholders engaged in the creation and development of Finnish SCDTs. By 2035, the research findings were presented help to facilitate resilient and sustainable socio-technical transitions in Finnish smart cities. Also findings were provided to pave the possible pathways towards Finnish National Digital Twin programme by exploring current issues and futurizing knowledge to future-oriented policy innovations and the promising integration of DTs and Futures Studies tools.

1.4 Thesis Structure

The thesis was divided into four chapters, each of which contributes to a thorough knowledge of Smart City Digital Twins (SCDTs) and their role in constructing resilient urban futures in Finland. The first chapter offers an outline of the research's focus and sets the context for the current debates. It explains the research questions and objectives, specifies the scope of the study, and summarises the overall structure of the thesis, providing readers with an overview of the research.

Chapter 2 explores the conceptual underpinnings and literature examination, laying the scientific foundations for the study. It delves into vital concepts like socio-technical transitions and the multi-level perspective, giving an analytical foundation to comprehend SCDTs socio-technical transformations. Smart cities were discussed in terms of their progress, conceptualization approaches, and other dimensions. Furthermore, the Smart City Digital Twins sub-chapter investigates the conceptual roots of Digital Twins, possible advantages, and obstacles in integrating them into cities. The findings of the literature review in this chapter are also part of the IPRM process in the research method chapter. Intentionally, the literature review was maintained distinct to offer the reader a clean flow of knowledge for reasoning the logic of IPRM components.

In Chapter 3, the research method and analysis part, the selected method Innovation Policy Roadmapping (IPRM) was explained. This chapter outlines the IPRM method, including how data was collected and multi-level expert insights were analysed. In this chapter, findings and multi-level analysis were fused to keep the integrity of the research so that, it provides a thorough examination of the collected secondary data, findings during roadmapping process, including drivers, policies, sectoral changes, and a technological roadmap and fused with primary data, expert insight analysis at the macro, meso, and micro levels. The chapter also tackles research limits and ethical concerns, offering a comprehensive view of the depth of the study.

Chapter 4 – Discussion and Conclusion, dives into the synergy between Futures Studies methodologies and SCDTs, examining the possibility of their combined use in envisioning sustainable urban futures. Finally, in the conclusion, the observations, and arguments from the prior chapters were synthesised. It emphasises the transformative potential of SCDTs in Finnish urban environments, proposes future research areas, and indicates outstanding issues that contribute to the advancement of SCDTs as transformative instruments for developing sustainable and versatile urban futures. It offers a cohesive and thorough examination of SCDTs, bringing readers through their conceptual foundations, practical consequences, and potential future applications.

2 Conceptual Foundations and Literature Review

The General literature assessment was conducted in the initial stages via Scopus database in addition to the university's library engine Volter with the keywords: "smart city" and "smart cities" until the end of 2022. Total number of documents were 41.164 within period of 1997 – 2022. Although the term "smart cities" first coined by Vineeta Shetty with an article titled "A tale of smart cities" in Communications International Journal in 1997, results have shown that the concept "smart city" found its initial foundations by which a published article named "Smart Cities: The Singapore Case" in the journal of Cities in 1999 (Mahizhnan, 1999).

When the Boolean Operator "(TITLE-ABS-KEY ("smart city" OR "Smart City Digital Twin") AND TITLE-ABS-KEY ("finland" OR "Finnish")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "bk") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English")" was used for research up to 2022 in Finland as of literature scanning began for this study. After reviewing the initial literature that can provide answers to the first research question within the scope of the research, the result did not reach 50. Considering the scope and objectives of the research, geographical and thematic research gap on the Finnish SCDT was observed and IPRM was never utilized in the SCDT phenomenon within the scope of future research.

After initial screening, it was also realized that the broad subject areas were integrated "smart city" for example mathematics, engineering, medicine and even genetics. Thus, with the study's research goals in mind, a Systematic Literature Review – (SLR) was conducted. Resulted papers built guiding research materials. Moreover, in some sections cross-referencing was also applied during desktop studies of IPRM such as organizational reports in organizational websites. The literatures were reviewed via Volter and Scopus by limiting the year range from beginning to the end of 2022. The Boolean operation in Scopus was TITLE-ABS-KEY ("smart city" OR "Smart Cities" AND "Digital Twin" OR "Urban Twin" OR "City Twin").

Before providing literature findings, the essential reasonings behind socio-technical transitions were given to the reader in the following conceptual foundations section. It builds systems-thinking foundations behind SCDT perspectives used in the literature. Whether actual improvements in Finnish SCs differ from one another, this section ponders what clarifications can be provided by using IPRM within the milieu of SCDT systems thinking, and what policy innovations and sectoral bundles are needed for Finland's SCDT socio-technical transformation.

2.1 Conceptual Foundations

2.1.1 Socio-technical Transitions

The interaction of societies is greatly facilitated by technological advancements. Even if it is still uncertain how the continuous structural nature of technology integrations in today's world will affect societies in the long run, we may examine historical developments and anticipate future-oriented technological transformation trajectories. Technological Transitions (TT) "[…] are defined as major technological transformations in the way societal functions such as transportation, communication, housing, feeding, are fulfilled." (Geels 2002, 1257). In the same study, Geels ponders on the vital questions "How technological transitions come about? Are there particular patterns and mechanisms in transition processes?" Now, when we go back to the definition of TT, it can be stated that the cities which are the biggest actors of service obligations such as transport, urban retrofitting, energy, water, and waste management, are going through systemic transformations by using the state-of-the-art technological solutions in their services.

Clustering the systemic dynamics in cities into two main lines, supply-side sectoral innovations, and demand-side configurations to alleviate pressure on cities can be explained by the historical articulation of urban services. If societal functionalities are fulfilled by technological reconfigurations (Geels, 2002; 2004; 2006) and the societal systems thinking has been advanced by technological transformations in city services, then socio-technical systems thinking is indispensable to analyse complexity of socio-technical transformations in cities. That was one of the main objectives of this research.

Geels (2002) illustrated the multi-level perspective – MLP to answer above mentioned questions empirically based on a qualitative longitudinal case study. In analysing socio-technological configurations, the multi-level perspective was built its ontological foundations on concepts from evolutionary perspectives and technological regimes as well as multi-layered approach on technological change (Rip & Kemp, 1998) because according to Geels (2002) TT encompasses not just technological advances, but also changes in user practises, legislation, industrial relationships, infrastructure, and symbolic significance or culture.

Since "system innovations are complex, uncertain and involve multiple social groups" (Geels, 2006, 178), and MLP is "[…] an analytical and heuristic framework to understand TT" (Geels, 2002, 1273), in parallel to the main context of the research, MLP was chosen to provide conceptual foundations of this research as well as an analytical tool to analyse systemic transformations of the future SCDTs and to reduce the complexity of these socio-technical changes in Finnish cities to some extent. Although, MLP is not capable to provide new policy tools, it signifies a general framework for an enhanced configuration of existing policy instruments (Geels, 2006).

2.1.2 Multi-level Perspective

There are global and local models in the Multi-Level Perspective (MLP). The former analyses the general course of socio-technical changes using three analytical levels and multiple temporal phases, whereas the latter focuses on specific activities and causal processes in multi-level interactions (Geels, 2019; Geels & Schot, 2007). While a holistic global model analysis may be used to examine long-term socio-technical transformations brought on by climate change on a wider scale, local model can also be used to examine the effects of the landscape drivers on socio-technical system. For instance, Fryszman et al. (2019) use the local model of MLP to examine the effects of urbanisation developments on socio-technical transformations of city smart mobility systems, whereas Geels et al. (2017) use the global model of MLP for innovation policy analyses on decarbonization socio-technical transitions against climate change. Depending on the vantage point of the analysis of the pressure that socio-technical regimes may be exposed to considering landscape alterations, local or global MLP may be utilised.

MLP includes three levels: technological niches, socio-technical regimes, and landscape (See **Figure 1**). Technological niches inherently represent novelties, but these novelties by themselves does not perform directly systemic transformations. On the contrary, landscape developments such as demographic trends, climate change and urbanization may generate tensions and certain problems on socio-technical regimes and their inadequacies attract novelties in niche level. For example, Geels (2006) argues that the resulting tension is particularly crucial for the emergence of radical innovations because niches are vital for system innovations and transformations, as he delineate them as seeds of change. These innovations, which are essentially triggered at the niche level, are expected to be clustered for the process and used in socio-technical regimes or even replace them and eventually transform the landscape (Geels 2002, 1262). However, novelties may experience mismatch and fail due to the institutional, political, economic, and even culturally rooted structure of these regimes.

Niches are secured areas like R&D facilities, funded pilot projects, or tiny market niches where users have needs against pressure from landscape developments and are eager to support new technologies provided by such entrepreneurs and start-ups focusing on novel concepts that deviate from the status quo (Geels, 2011).

Socio-technical regimes are perhaps the most noteworthy level of MLP that is epistemologically challenging to grasp. While Rip & Kemp (1998, 340) define technological regime as "A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures", (Geels 2002, 1260) critically argues that the technological trajectory is shaped not only by engineers and technical practitioners but also by a “multi-actor network” of market and users, policymakers, societal groups, industry, scientists, researchers and conceptualize their interactions as socio-technical regimes. According to Geels (2004, 905) it is possible to group them in technological, science, policy, socio-cultural, user and market regimes sharing similar goals, values, and problem-solving agendas in their context. Thus, meta-coordination through those socio-technical regimes is needed for coherent dynamic integrations (Ibid, 905). Socio-technical regimes include features such as being locked into specific patterns, where innovation occurs gradually through small modifications that accumulate into consistent orientations. The refers to the partially unified set of norms that guide and harmonise the behaviour of social groups in charge of maintaining the various parts of socio-technical systems (Geels 2011).

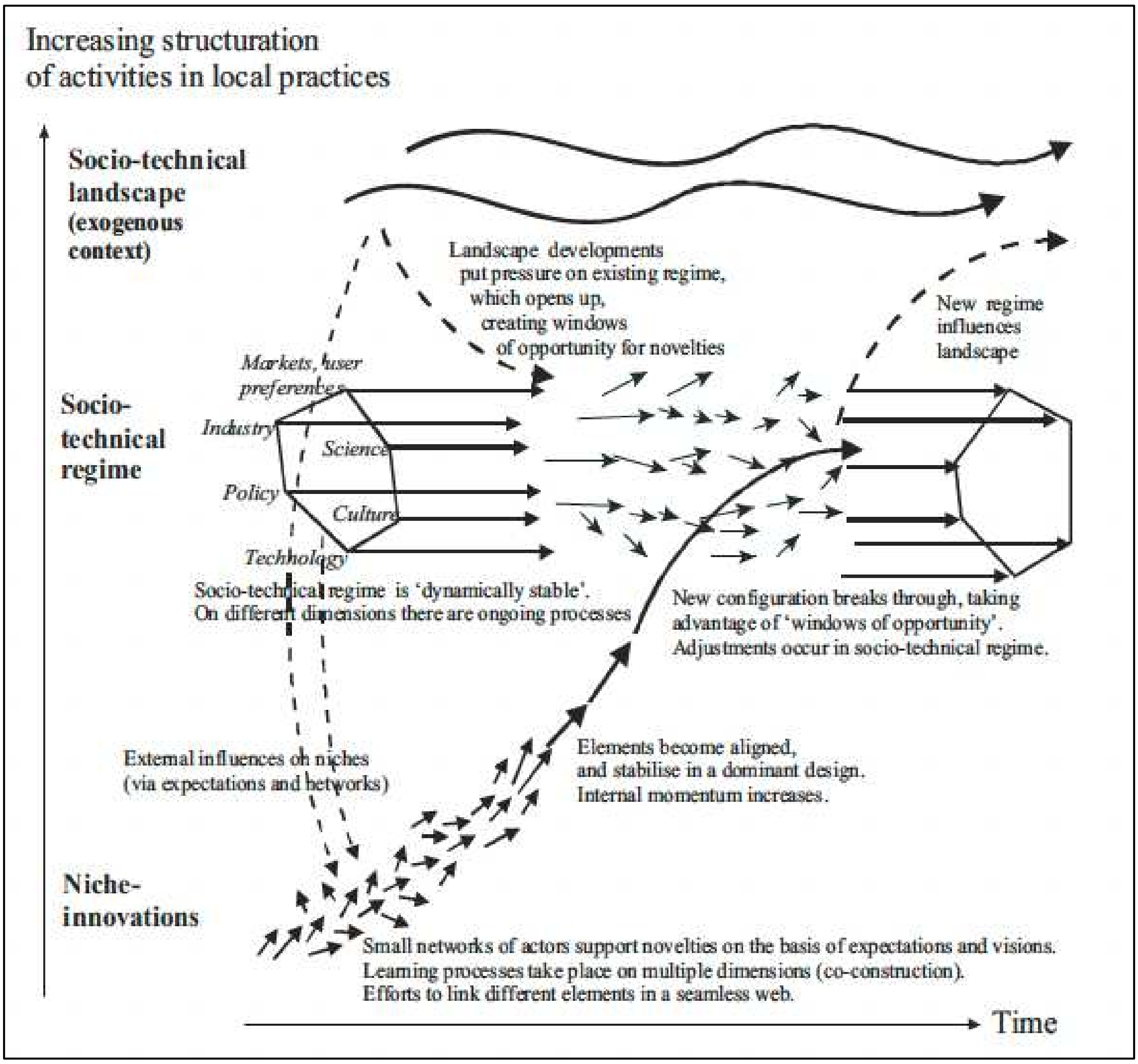

Figure 1. Multi-level perspective on transitions (Geels & Schot, 2007, 401. Origins: Geels, 2002, 1263).

Socio-technical systems are “the artefacts and material networks” (Geels 2004, 911), “stabilized by regimes that coordinate the activities of actors and social groups” (Geels 2006, 170). Existing systems are stabilised due to the retrospective alignments between technology, regulations, user trends, services, and cultural discourses built over the years (Geels, 2019). The perceptions, rules, and actions of socio-technical systems' regime actors, such as companies, entrepreneurs, experts, individuals and costumers, policymakers, and special interest groups reproduce, maintain, and progressively enhance those socio-technical systems. Moreover, socio-technical systems are artefacts of holistic configuration and broader interactions, and they are characterized with dynamic stability, thus, difficult to change. Geels (2004, 2006, 2019) emphasise sunk investments in infrastructure, skills, technological lock-ins, inertia, and path dependencies as major reasons for resistance to change.

Landscape level refers to “set of deep structural trends” (Geels 2002, 1260). “Landscapes are beyond the direct influence of actors and cannot be changed at will. Material environments, shared cultural beliefs, symbols and values are hard to deviate from.” (Geels 2004, 913). Socio-technical landscape, in its simplest form, relates to elements of broader exogenous drivers such as urbanisation, population trends, climate change, and cultural changes (Geels, 2006).

In sum, socio-technical transitions are the “transitions come about through interactions between processes at these three levels: (a) niche-innovations build up internal momentum, through learning processes, price/performance improvements, and support from powerful groups, (b) changes at the landscape level create pressure on the regime and (c) destabilisation of the regime creates windows of opportunity for niche innovations.” (Geels & Schot 2007, 400).

Pressure, Tension and Windows of Opportunity

Landscape developments and "specific shocks" in landscape (Geels & Schot, 2007, 410) render socio-technical systems to adopt systemic changes yet the inertial nature of socio-technical regimes of those systems due to the dynamic stability causes tensions and subsequent pressures in socio-technical systems, but also opens windows to new opportunities for radical and incremental innovations. For instance, the pressure that climate change is presently exerting on the transportation and energy sectors is leading to changes in governmental policies as well as technical search strategies (Geels, 2004). This pressure however may also be created by significant shifts in political alliances, cultural norms, and ideologies within the socio-technical regimes.

Although MLP conceptualises socio-technical transitions at three analytical levels in general terms, the shifting dynamics of the landscape developments require “sustainable” systemic transformations. For example, according to Geels (2010) the lack of shared vision within socio-technical system and their sub-regimes hinders sustainable transitions. “Actors not only have different interpretations of the right balance between social, economic and environmental sustainability, but also have different rankings of environmental problems and hold different views about the (dis)advantages of particular solutions and the most appropriate policy packages." (Geels 2010, pg. 500). In the same vein, Smith et al. (2005) claim that altering pressures on regimes lead them to endeavour transformation in different directions since regimes' capacities, skills and resources can be imbalanced, they suggest that it is vital to articulate regime selection pressures (See **Table 1**) for regimes to direct sustainable transition coherently by referring "adaptive capacity in regime transformation" (Smith et al., 2005, 1496).

If socio-technical system's regime actors embrace the shared vision by regime selection pressures, regimes become able to adapt to demands for selection pressures. Essentially, regime selection pressure can lead new dimensions in the context of Finnish SCDTs, as innovative sustainable socio-technical transitions in Finnish smart cities aim to optimize urban systems, foster sustainability, and drive future-oriented urban innovations.

Table 1. Causes of regime selection pressure (Adopted from Smith et al., 2005, 1496).

The creation within niches of novel socio-technical configurations
An innovation that seeds a transformation in a 'spanning' regime
The spur to innovation felt through competition from another socio-technical regime serving the same or overlapping markets
Emergence of alternative 'visions' of the future
The generation of changes in the social landscape that put the regime in tension
Public debates targeted at changing socio-technical regimes

MLP and Transition Pathways

MLP offers transition pathways (See **Table 2)**. This allows interpretations for comparative study to illuminate the reasons why transitions occur at various paces and with different characteristics in different counties, regions, and cities (Geels, 2019). MLP's alignment in transition as well as policy-instrument is crucial since it gives useful analytical support for innovation policies correlated with gathered data regarding the research's primary objectives. For example, regimes under pressure from landscape changes may use diverse strategies to adapt and local practices could change as a result. Hence, public bodies may create new policy plans, users can change their behaviours, and companies adopt new sectoral strategic investment plans.

There are several policy instruments that come from three distinct governance paradigms: the traditional top-down model, with hierarchical relationships and a central role for (national) government; the bottom-up model, with considerable autonomy for local actors; and the policy networks model, with interconnected actors and differing values and beliefs (Geels, 2006). These three governance paradigms come from various disciplinary backgrounds, emphasise various topics, incorporate various ideas about how the government interacts with other actors, and suggest various policy tools. In this situation, MLP has the capacity to present coordinated policy transition pathways connecting those diverse regimes actors. For example, Smith et al. (2005) recognise that four regime transition is a result of two dimensions: (1) changing pressures on the regime's selection, and (2) coordination of resources from both inside and outside the regime that may be used to respond to these pressures. However, Geels & Schot (2007) emphasise the temporality and nature of MLP alignment to transition and differentiate four transition pathways.

Table 2. Transition Pathway Typologies and Explanations (Adopted from Geels, 2011, 32, 2019, 194; Geels & Schot, 2007, 406–413; Smith et al., 2005, 1499–1502).

Transformation Pathways	Characteristics	Explanation
Endogenous renewal	Coordinated response, internal adaptation	It occurs when participants of a regime (firms, supply chains, clients, and regulators) actively seek out strategies that address perceived competitive challenges to a regime.
Re-orientation of trajectories	Uncoordinated response, internal adaptation	It is the outcome of an external or internal shock, followed by a response from regime actors employing internal resources. Internal processes can drastically alter change trajectories without causing discontinuities in the regime.
Emergent transformation	Uncoordinated response, external adaptation	It results from unexpected forces from outside the regime, which are frequently led by small and innovative enterprises.
Purposive transitions	Coordinated response external adaptation	They are deliberate and well-coordinated transformation processes that come from outside the current regime.

Transformation	Niches are not developed	Landscape changes put strain on the regime's "disruptive change" along this path. Niche inventions are still underdeveloped. Existing actors change the direction of innovative trajectories, which leads to gradual changes in the regimes of the forces affecting the landscape.
Reconfiguration	Niches are more developed and symbiotic	Landscape developments put pressure on regimes, this path sees the creation of niche innovations. If niches are mutually beneficial to the regime, dominant entities may utilise them as 'add-ons' to address local issues.
Technological substitution	Niches are well developed and competitive	High pressure of landscape transformations on regimes. Competitive niche innovations flourish. Tensions inside the regime create a window of opportunity for the emergence of niche innovations that might take the place of the regime.
De-alignment and re-alignment	Multiple niche Avalanche	Major landscape stresses initially create regime collapse (de-alignment). Taking advantage of this space, numerous niche innovations arise, coexisting over lengthy periods of time (causing uncertainty about which one would emerge as the victor). Re-alignment processes eventually develop around a single concept, resulting in a new regime.

Geels (2019) emphasises the importance of policy analysis and proposes that through transformation pathways, within socio-technical regimes, authorities should organise and encourage interactions between actors, instructional procedures, and information exchange. Hence, he adds, early transition periods of system transformations typically have the greatest importance for policy instruments to encourage learning, network building, and visioning (Geels, 2019). In the same vein, regarding MLP which put emphasis on "windows of opportunities", according to Geels (2006) policy makers cannot simply "force" big changes into stable socio-technical regimes, but they may encourage diversity at the niche level and attempt to modify current processes in the regime with the goal of creating links between the two levels. For example, despite top-down policy model, horizontal policy coordination can facilitate exploration of synergies and mismatches across policies in addition to shifting focus away from single policy instrument in regimes (Geels, 2006, 2019).

2.2 Smart Cities

2.2.1 Overview of Smart City Emergence

Amid climate change, data economy, increasing urbanization and relocation of population set high expectations on cities in terms of aspects such as long-term innovation green transformations and increasing resilience of cities to future uncertainties. According to current estimates on the future of cities, approximately 70% of the world's population will be living in cities by 2050 (*World Cities Report 2022: Envisaging the Future of Cities*, 2022). These rising pressures need the use of Internet and Communications Technologies – ICTs into city service operations. Future solutions based on smart control, monitoring, and automation, for example, in cities, traffic congestion and waste control and logistics, will require novelties on real-time Geographic Information Systems – GIS (Finnish Government Finland's Digital Compass, 2022).

This factor dominating today's academic and public debates, preserves its effects on the continuous technological transformation of city operations in recent decades. While these factors affecting the systemic transformations of urban services triggered the integration of innovations into the city systems, they also influenced the definitions and conceptualisation efforts of "smart cities" that we discuss recently.

As retrospective analyses reveal, due to the exogenous developments, cities systemic responds to these transformations have led scholars to label the concept of the "city" to "wired cities" (Dutton et al., 1987), "cyber cities" (Graham & Marvin, 1999), "digital cities" (Ishida et al., 2000), "intelligent cities" (Komninos, 2002), and Hollands (2008) labelled it as "smart cities" and recently "smart city digital twins" (Mohammadi & Taylor, 2017; Albino et al., 2015; Peirce et al., 2013).

Origins of Modern "Smart City" Phenomenon

Researchers relate the origins of modern "smart cities" which first appeared in the 1990s, to systemic changes that began in the United States in the mid-1800s (Peirce et al., 2013; Yigitcanlar et al., 2018). The laborious task of tracking population and economic dynamics began to put pressure on the federal government because all these registration and monitoring processes were done manually at the time (Peirce et al., 2013). Increasing pressure and mismatches between the management of economic dynamics such as expanding population, production, and logistics and the ineffectiveness of the government in 1880s created windows of opportunity and led Herman Hollerith to design a mechanical tabulating machine to speed up the counting. Then, he founded the Computing-Tabulating-Recording Company, now known as IBM – International Business Machines.

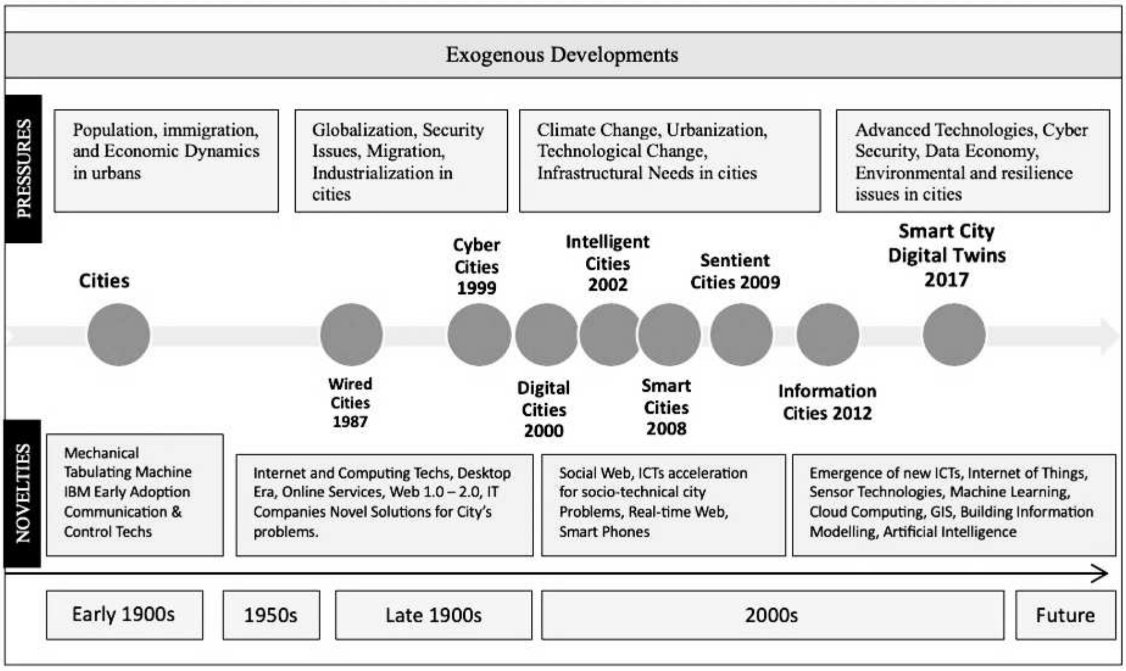

Figure 2. Brief Retrospective Exemplification of Pressures and Tech Novelties impact on City Transformations' Definition and Conceptualizations: "City" to "Future City x" (Albino et al., 2015; Batty, 2018; Deren et al., 2021; Lombardi et al., 2012; Mohammadi & Taylor, 2017; Peirce et al., 2013).

Since then, the necessity for enhanced public services against landscape developments has never been slow down (See **Figure 2**). With differing pressures and novelties, the growth of computer technology and ICT, the involvement of big IT corporations, and citizens' demand for digital applications all paved the emergence of smart cities over time (Albino et al., 2015; Bakıcı et al., 2013; Lombardi et al., 2012; Montes, 2020; Peirce et al., 2013). Growing urban populations and complexity need improved novel tools and more efficient public services. For example, computing technologies, internet (Web 1.0 – 2.0 – 3.0), and ICT grew in popularity among technology enthusiasts and forward-thinking governments and dynamic inventive cities. Hence, major IT corporations such as IBM, Nokia, Microsoft, Cisco, and Siemens, saw these windows of opportunities to enhance urban management with novelties while also entering an unexplored market. City's socio-technical regime actors such as researchers, policy makers, industries, citizens, and entrepreneurs welcomed bottom-up SC efforts, harnessing the ICTs, cell phones, and readily available online data, motivated by a desire to improve the liveability of their cities which turned todays' "Smart Cities" and maybe "X" city in the future. Clearly, due to all the systemic changes in cities caused by external development's pressures and niche novelties, numerous descriptive and conceptual approaches with distinct viewpoints on cities have found a place in the literature.

2.2.2 Definition and Conceptualization Approaches

"Smart cities" is *still* a fuzzy concept. Attempts to label how cities are smart based on their integration of ICTs into their services have been a topic of great debate in various disciplines since the early 2000s. The increasing impact of ICTs on the systemic transformations of cities and the consequent integration of these new configurations into the urban systems have led to differentiations in the attempts to define and conceptualize it. However, there is no universally accepted definition of smart cities (See, **Table 3**).

While some researchers describe as superficial these "self-congratulatory" labelling efforts (Hollands, 2008; Caragliu et al. 2011, 69), others have argued that terms such as wired, cyber, digital, and intelligent, based on infrastructure and enabling technologies, externalize the human factor (Allwinkle & Cruickshank, 2011; Caragliu et al., 2011; Lombardi et al., 2012). For example, Hollands (2008) emphasize a critical perspective to retrospective labelling attempts and demonstrates the vital requirement to begin with people's current knowledges and abilities rather than with technology in general. Similarly, Caragliu et al. (2011) conducted quantitative statistical studies with a critical attitude towards ways in which technology is at the forefront on the premise of the smartness of cities, and their study demonstrated a positive relationship between urban growth and human capital. Albino et al. (2015) conducts in-depth literature research of the terminological meaning of "smart" in the urban context indicating that "smart" is based on concepts where technology is at the forefront in defining the smartness of the city. Evidently, it seems that defining smart cities will keep the agenda for a long time since recent studies also reveal that there still exist a common focus a monocentric technology focus and various perspective among academia, organizations/governmental and industry in SC conceptualization attempts (Toli & Murtagh, 2020; Yigitcanlar et al., 2018)

Table 3. Various smart city definition examples (Adopted from Albino et al., 2015; Yigitcanlar et al., 2018)[1]

Definition	Source
Smart city as a high-tech intensive and advanced city that connects people, information and city elements using new technologies to create a sustainable, greener city, competitive and innovative commerce, and an increased life quality.	(Bakıcı et al., 2013)
A city is smart when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance.	(Caragliu et al., 2011)
Smart city generally refers to the search and identification of intelligent solutions which allow modern cities to enhance the quality of the services provided to citizens by a forward-looking way in economy, people, governance, mobility, environment, and living.	(Giffinger et al., 2007)
The application of information and communications technology (ICT) with their effects on human capital/education, social and relational capital, and environmental issues is often indicated by the notion of smart city.	(Lombardi et al., 2012)
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 business.	(European Commission)
A digital landscape of connected sensors and devices creates millions of control endpoints generating real-time data during operations and facilitating automated actions.	(Nokia)
A collection of technological systems that help cities to achieve their goals. Smart cities provide a higher standard of living for people without burdening the environment. The goal is to build a better society: healthy, safe, and adaptable cities that provide their residents with services, energy, housing, and transport solutions.	(VTT - Technical Research Centre of Finland)

[1] Smart City definitions in the context of Finland were added.

The city is a "system of systems". Smarter cities transform their systems and their "system of systems". A smarter city is one that uses technology to transform its core systems and optimize the return from largely finite resources.	(IBM, 1999)
Smart cities use technology and innovation to improve the urban environment – leading to improved quality of life, greater prosperity, and sustainability, and engaged and empowered citizens.	(UNDP)
A smart city uses digital technology to improve its performance, liveability, and the well-being of its citizens. New technology and data are used for solving the cities' economic, social, and environmental challenges.	(Business Finland & Tekes)
Nordic smart cities are unbounded, regenerative, and vision-driven, which leads to a unique – even radical – view of what it means to be" people-centric". Characteristics of cities are used here to make technology the servant, not the master of people.	(Demos Helsinki 2020)
An urban area that has become more efficient and/or more environmentally friendly and/or more socially inclusive using digital technologies.	(Nordic Smart City Network, 2021)
Smart city is a city that, based on modern information and communication technologies, integrates economy, people, living, environment, governance, and mobility.	(Kozlowski & Suwar, 2021)

Through typological and conceptual investigations, researchers have attempted to make sense of the mismatches in the notion of smart cities. Kozlowski & Suwar (2021, 510–512), for example, has found three types of definitions in their substantial literature and case studies on municipal authorities aiming to make their cities smart; (i) *techno-centric* that connects the city to technologies (technocratic), (ii) *human-centric* linked to people's education, learning, and knowledge, which some writers identify as fundamental drivers driving city growth and, (iii) *hybrid* they connect the SC's technical, human, and institutional components. **Table 3** provides evidence of this typology. Demos Helsinki, for example, characterizes notion of smart cities as human-centric by characterizing technology as "servant", Nokia as techno-centric, and the European Commission as hybrid. In the same vein, recent study on the mismatches of 50 organization and research institutions in framing smart cities reveals three different approaches; (i) *ontological*, attempting to describe the main components of a SC by defining what a SC is both literally and discursively (policy and strategy), (ii) *epistemological*, SC is defined by how it is approached and operationalized, (iii) *bibliometric*, synthesize how a SC is defined in the literature and develop a *meta-definition* (Kitchin, 2022, 56). Clearly, typological, and conceptual studies have revealed that there are misalignments in the concept of smart cities. However, these discrepancies have prompted scholars to investigate for compatibility with other fields and frameworks.

2.2.3 Dimensional Approaches on Smart Cities

Although there is no common definition, there is a wide consensus on accepting six dimensions on smart cities (see **Table 4**); economy, environment, mobility, people, governance and living (Albino et al., 2015; Caragliu et al., 2011; Giffinger et al., 2007; Kozlowski & Suwar, 2021; Lombardi et al., 2012; Toli & Murtagh, 2020). It is possible to emphasise that cities adapt their systemic components, notably ICTs, during the transition phase. For example, we may underline that the shift in urban mobility dynamics triggered by climate change pressure gradually impacts other city components such as the environment and governance systems of cities, eventually permitting systemic clusters. These characteristics are based on concepts such as local competitiveness, ICT, economic variables, natural resources, human and societal assets, living standards, and public participation in local governance (Kozlowski & Suwar, 2021, 513; Lombardi et al., 2012, 138). These six dimensions also form the structural basis for assessing tools. For instance, in 2007, University of Vienna in 2007 developed the first of its kind SC evaluation metrics to assess 70 European medium-sized cities (Giffinger et al., 2007). To underline, Turku, Tampere, and Oulu were placed third, sixth, and seventh, respectively, among these 70 cities.

Table 4. Six smart city dimensions (Adopted from Kozlowski & Suwar, 2021).

Dimensions	Definition
Smart Economy	By concentrating on innovation, entrepreneurship, trademarks, productivity, and labour market flexibility, as well as integration into the domestic market, the term "smart economy" describes the competitiveness of the city. Information and communication technologies (ICT) are utilised to advance e-business and e-commerce, as well as to improve chances for innovation, manufacturing, and service delivery, as well as the development of new goods, services, and business models.

Smart Environment	It covers urban natural environments (like green spaces), resource management (like recycling and resource replacement), and environmental preservation. Effective waste management, the utilisation of renewable energy sources, and environmentally friendly urban design are just a few examples of solutions demonstrating a smart environment. Technologies of information and communication are employed to enhance the ecological systems of the city.
Smart Mobility	It refers to the accessibility and availability of services, information and communication technology, and environmentally friendly transportation.
Smart Governance	It is primarily defined by effective and efficient public administration, high-quality public services, and local involvement in city decision-making. Information and communication technologies are employed in e-administration to assist public authorities' decisions and to enhance democratisation and service delivery.
Smart Living	It highlights several facets of living quality. By integrating ICTs into their daily operations, city officials improve the citizens' health, safety, culture, and living circumstances.
Smart People	This refers to the credentials and education of the city's residents, as well as social contacts connected to integration, participation in public life, and global openness. ICT helps individuals be more innovative and creative, as well as enhance access to education and training.

Evidently, this six-dimensional approach has spawned alternative framework and SC assessment approaches as well. For example, Lombardi et al. (2012) and Allwinkle & Cruickshank (2011) suggested the triple helix model for SC transitions by underlining the relevance of SC six components' interrelationships. This model is essentially a reference framework for the examination of knowledge-based innovation systems, and it links the complex and reciprocal interactions between the three primary organisations: universities, industry, and government. Other one is Boyd Cohen's well-known *Smart City Wheel* a smart city assessment and applied in many SC benchmarking cases with 62 indicators including six dimensions with sub-working areas. For instance, smart buildings, resources management and sustainable urban planning is covered under smart environment dimension with smart homes, carbon footprint, and waste generation indicators. Those indicators emphasise metrics such as waste generation indicator emphasise “total collected municipal solid waste city per capita”.

However, some scholars approach this six-dimensional perspective critically. Mentioning the inadequate addressing balanced and sustainable inclusion, for instance, Yigitcanlar et al. (2018, 149) developed *multidimensional smart city framework.* According to them smart cities are driven by three sorts of drivers: community, technology, and policy, which are related to five desired outcomes: productivity, sustainability, accessibility, wellness, liveability, and governance. These causes and outcomes combine to form a SC framework, with each representing a separate component of the SC concept (Ibid, 150). Similarly, Neirotti et al. (2014) divides prevalence of investments in those dimensions into hard and soft domains. Briefly while *hard domains* refer to physical assets such as buildings, ICT infrastructure and built technical settings, *soft domains* are education, policy, cultural, innovation, and social settings. Cities that undergo various transformations throughout the process and continue to evolve in terms of smartness. Thus, researchers appear to be attempting to develop hundreds of frameworks and models that take a critical or complementary approach to SC concepts that exist to gain a better understanding. However, it appears that at the stage of socio-technical transitions in cities, these six identified dimension in existing literatures will continue to exist for some time.

Cities have been pressured to find solutions to landscape challenges and find themselves in a perpetual systemic transition by exploiting increasingly evolving ICTs, which began with Herman Hollerith's mechanical tabulating machine. While external factors change, innovations in technology shift through new niche breakthroughs, placing cities in a complex system phenomenon vulnerable to future uncertainties. In that sense, Batty et al. (2012) exemplifies particular needs as: generating a new knowledge of urban challenges; effective and feasible techniques of coordinating urban technology; models and methods for using urban data at many spatial and temporal dimensions; building new communication and distribution technologies; creating new models of urban government and organising highlighting essential challenges in cities, transportation, and energy; and recognising risks, uncertainties, and dangers in smart cities. Similarly, scholars believe that understanding this complex system needs entails a more holistic approach to urban concerns (Albino et al., 2015, 10; Kozlowski & Suwar, 2021, 512; Lombardi et al., 2012, 148; Yigitcanlar et al., 2018, 151). For example, a smart mobility system that seeks to optimise traffic flow with ICTs would not alleviate congestion; instead, it will necessitate shifting users from automobiles to public transport, cycling, and walking (Kitchin, 2022).

“A city is a complex system”, as complex systems, cities have unexpected tendencies, and when certain actions are taken, reactions and feedback may be gained (Lombardi et al., 2012, 144). In addition to landscape uncertainties, recent complex technological developments such as artificial intelligence (AI), machine learning (ML) and internet of things (IoT), make it critical that future smart cities are the key to meeting citizens' ever-increasing demands by utilising latest ICTs to empower better administration of available resources, but it could also pose challenges (Javed et al., 2022). Thus, in this complex system, scholars, practitioners, and organisations develops frameworks that suited their own specific practical perspectives rather than (generally) a generic framework outlining the complexities and links of various dimensions of smart cities in a comprehensive and simple manner (Yigitcanlar et al., 2018, 146). As a result, due to lack of common perspective, it also causes a divergence on the conceptualization of the city and how it operates among the stakeholders such as politicians, urban planners, architects, citizens, universities, economic actors, and public officials, who constitute the system dynamics of this city.

Aware of those facts, Finger & Razaghi (2017) propose conceptualization of cities as a complex and dynamic socio-technical system since it is more appropriate practical than the above partial or too abstract conceptualizations. Moreover, Geldenhuys et al. (2018) conceptualize cities as complex socio-technical systems – of – systems by emphasising holistic manner due to its interdependencies among dynamic city components. When considering smart cities in six dimensions, it is reasonable to assume that SC socio-technical system is formed by six interconnected socio-technical sub-systems (smart – environment, people, governance, mobility, economy and – living) and these sub-systems entail interrelated socio-technical regimes that form the dynamics of the main SC socio-technical system. Because a "smart progressive city needs and requires the input and contribution of these various groups of people..." (Hollands, 2008, 316), MLP's conceptual foundations and analytical approach for SC socio-technical systems-thinking are crucial here. For example, Finger & Razaghi (2017)'s conceptualization of smart cities as socio-technical systems includes two key elements: First, *technology push*, in which cities are pushed into fast-paced ICTs, and *demand-pull*, in which whether citizens can demand the most relevant ICTs for their desired functioning SC. The second is “*citizens* *or consumers*?" This focuses on the direction of SC services, whether they are produced for public benefit or for commercial gain. This is an important fact to consider if a holistic SC socio-technical transformation that is resilient to future uncertainties is to be realised, because the development of SC services appears to face new challenges if the regime stakeholders of the SC socio-technical system do not adopt a common conceptualisation approach.

SC socio-technical system transition patterns are highly dependent on its local context. This assumption is supported by the findings of Neirotti et al. (2014). They claim that the structural characteristics of cities impact city's digital trajectory, and that geographic location plays a part in SC strategy. Furthermore, population density, as well as the accompanying congestion challenges, may have a key role in deciding how SC deployment pathways are defined. Similarly, comprehensive case study analyses of municipalities' SC actions and initiatives show that, while urban authorities, communities, public institutions, and businesses all have a common interest in SC developments, the solutions they implement differ depending on their size, geographical location, or cultural environment (Kozlowski & Suwar, 2021). According to their findings, this is due to cultural variety, societal awareness, investment in hard and soft domains, and the degree of socioeconomic development of the country/region/city, which relates to available resources that may be deployed in SC regions. This can be briefly demonstrated based on climate change in the Finnish cities' context. For example, while the pressure derived from climate change affecting Turku's Smart and Wise smart city directions to be carbon neutral by 2029 and its one of the main city system drivers is having a port which increase the attention on mobility, in northern Finland, however, cities become vulnerable to the arrival of unfamiliar virus species because of their moist structural terrain increasing liveable circumstances for flies.

So, in this context their future SC transformation pathway and regime selection pressures and regime actors are different and should be different. It that case, local MLP model could be utilized to analyse the socio-technical transitions in cities and determine strategic policy guidelines with altering pressure selections and windows of opportunities for niche innovations in the Finnish local context.

The strain imposed by landscape transformations, along with the technological push exerted by contemporary high-tech advancements such as AI, ML, and IoTs, needs a holistic local SC conceptualisation. Boulanger's (2022) study on the drivers affecting smart cities before and after the Covid-19 pandemic, which can be described as a specific shock or disruptive change in 2019. The study reveals that smart cities accelerated their systemic transformations, but also recent shock have speeded concepts such as *smart city digital twins*, *metaverse city*, and *15-minute city*. In the same vein, Lu et al.'s (2019) research on 80 smart cities and technology readiness analysis offers a need for technical roadmap for robust future SC developments due to the causal interrelations of regimes, technology, and services. From this point of view, the need of analytical analysis of the SC socio-technical system transition and a holistic conceptual approach become apparent if a SCDT concept is to be adopted on the foundations of a robust and coherent SC.

2.3 Smart City Digital Twins

2.3.1 Digital Twins

DTs have become a popular topic of discussion in recent years, even though they have been there for around a half-century in various manifestations. Initially envisaged as a useful tool for engineers at National Aeronautical Space Administration – NASA in 1970s on Apollo 13 mission (GlobalData, 2020; Grieves & Vickers, 2016), the use of DTs has grown dramatically with Industry 4.0 (Raes et al., 2021), spanning a wide range of fields such as health, aviation, shipbuilding, and governmental administrations, among others (Deren et al., 2021). Notably, DTs are gradually gaining traction in the context of smart cities, owing primarily to the widespread deployment of Industry 4.0, IoT infrastructures and data economy, as well as advances in cutting-edge technologies; three-dimensional (3-D) modelling, AI, machine learning, and such visualisation technologies (Virtual Reality – VR, Augmented Reality – AR, and Extended Reality – XR) (Eleftheriou & Anagnostopoulos, 2022; Kaivo-oja et al., 2020; Zheng et al., 2019).

While the DTs were based on the conceptual systems thinking of engineering product lifecycle management in NASA's Apollo 13 mission, terminological initiatives have seen the light of day for the last two decades (See, **Figure 3**). Grieves coined the original terminology at University of Michigan Executive Course on Product Lifecycle Management (PLM) in 2003, "digital representations of actual physical products", which was later recorded in a "Digital Twin White Paper" that laid the groundwork for the creation of DTs (Grieves, 2014). The NASA published a document titled "The Digital

Twin Paradigm for Future NASA and U.S. Air Force Vehicles" in 2012, establishing a crucial milestone for defining DTs. Cities such as Singapore built virtual 3D representations of their Building Information Modelling - BIM in 2014 as frameworks for DTs matured in SC domain (GlobalData, 2020). BIMs recognises the origin of an urban DT, and they are precise representations of the built environment that include building assets, geographical and topological linkages with GIS, and extensive information about their physical infrastructure (Lehtola et al., 2022).

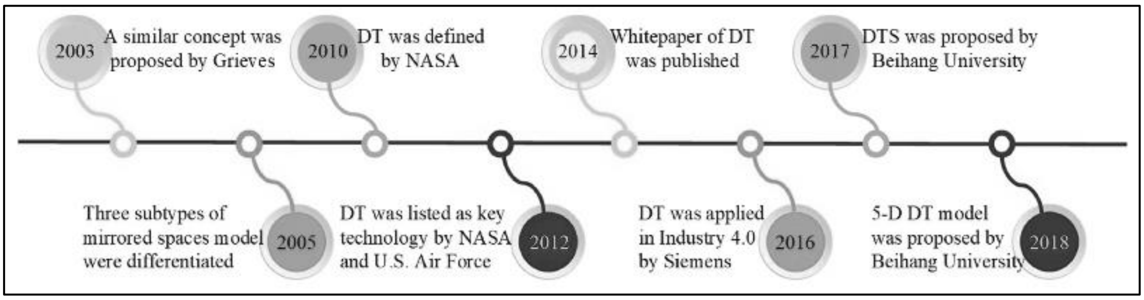

Figure 3. The milestone of digital twin development (Qi et al., 2021, 4).

The growing impact of sensor technologies and IoT on the industrial domain, which triggered Industry 4.0, as well as the demands of multinational corporations for systemic transformation, have aided corporate behemoths such as Siemens, Dassault Systèmes, IBM, and Microsoft in spreading the DT. When Singapore started preparing to pioneer city-scale DT in 2014, there were only a few businesses working in the DT field, with Dassault Systèmes being the most visible. As a result, a slew of goods dubbed "digital twin platforms" appeared in city-scale DTs.

Characterization and Definition Approaches

While Grieves (2014, 1) defines a digital twin as a "virtual representation of what has been produced," White et al. (2021, 1) take a broader view: "A digital twin is a digital representation of a physical process, person, place, system, or device." Zheng et al. (2019) take the definitional approach one step further and conceptualises the DT in a broad sense and a narrow sense. According to them, in a nutshell, DT in the narrow sense, is a collection of virtual information that fully characterises a possible or actual physical entity from micro-atomic to macro-geometric levels. In a broad sense, DT is an integrated Cyber-Physical System – CPS that combines virtual and physical space. Consequently, DT as a CPS can simulate, monitor, compute, organise and control the system, state, and process (Ibid).

Although the conceptual approaches to the digitally represented "thing" vary depending on the field of use of the DT application. In industrial domain the “thing” could be car, and in health it can be a person. As depicted in **Figure 4**, the DT essentially consists of three main components a) physical products, systems, place or person in real space, b) virtual representation of those products, systems, place, or person in virtual space, and c) characteristics of data and information flow that connect the virtual and real space (Grieves, 2014).

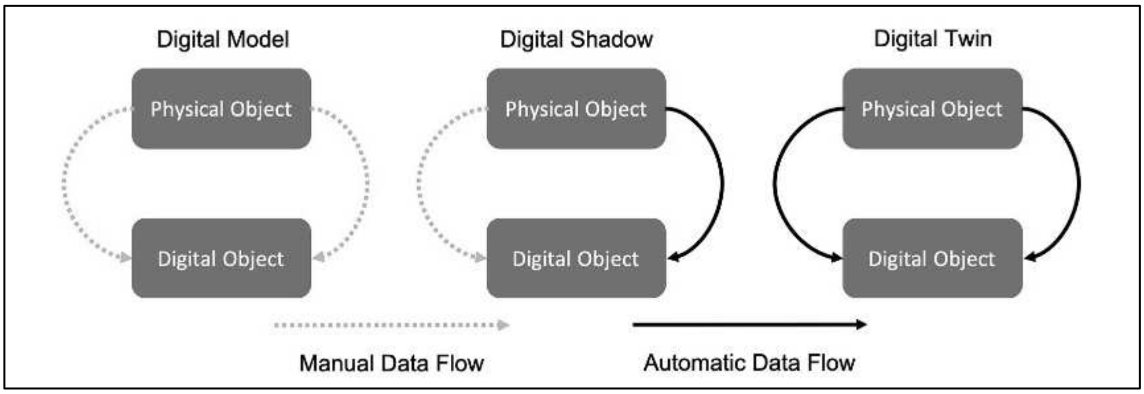

Figure 4. Smart city cyber-physical system characteristics: Digital Model, Digital Shadow, and Digital Twin (Fuller et al., 2020, 3; Mylonas et al., 2021; Zheng et al., 2019).

Despite ever-changing definitional approaches on DTs since 2004, while defining CPSs of virtual and physical spaces, there exists misconceptions (Fuller et al., 2020). For example, according to Ferré-Bigorra et al. (2022), it is due to early adoption stage and published literature is scarce, thus, it is seen in the widespread usage of the phrase "urban DT" to refer to a 3D digital representation – Digital Model of a city. DTs may imply various things to different industries, disciplines, and domains, but they all have one thing in common: data flow is at the heart of them (CDBB, 2021). However, academic, and theoretical definitions of digital model, digital shadow, and DT are proposed to help us define CPSs depending on the degree of "dynamic information flow in real time." (See, **Table 5**) (Eleftheriou & Anagnostopoulos, 2022; Fuller et al., 2020).

Table 5. Classification of Cyber-Physical Systems based on the degree of dynamic data-flow in real-time and exemplifications in Smart City Context (Modified from Eleftheriou & Anagnostopoulos, 2022; Fuller et al., 2020)

Digital Model	It is a representation of a physical object, such as blueprints or plans, that *do not exchange data automatically.* Physical object changes have no effect on the digital model, and vice versa. It is often a customizable 3D representation, but there is no automatic data flow between the digital model and the physical entity. Changes in one entity do not automatically affect the other when data is exchanged manually. **Exemplification in the context of smart city:** A digital model might be a precise 3D representation of urban infrastructure such as buildings, roads, and parks. This digital model enables city planners to see and analyse many elements of the city's structure, as well as simulate urban growth and create optimal transit routes. Then new model dynamics should be added in digital model manually.
Digital Shadow	It is a digital representation of a physical object including an ***automatic data flow*** from the physical object to the digital representation. The physical object's state and condition define the present status of the digital object, but not vice versa. It denotes a ***unidirectional data flow*** in which any changes to the physical object result in accordance updates to the digital representation, whereas changes to the digital object have no effect on the physical object. **Exemplification in the context of smart city:** A digital shadow might be a real-time data-driven representation of a specific region or component of the city. For example, data on air quality, traffic congestion, energy use, and waste management in a specific neighbourhood may be collected using sensors and IoT devices. This data is constantly updated and acts as a digital shadow of the area's present circumstances and performance in virtual space.
Digital Twin	A DT is essentially a completely integrated CPS, and the data has is ***bidirectional*** in which changes to either the physical or digital entity instantly results in matching changes to the other. This means that modifications to the physical object can cause updates to the digital body and vice versa. The digital representation in a DT not only gets information from the physical object, but it also has the capacity to control and affect the physical entity. **Exemplification in the context of smart city:** A DT of a smart city water distribution system. The virtual depiction of the full water network, including pipes, valves, pumps, and reservoirs, would be the DT in virtual space. It would capture real-time data on water flow, pressure levels, and quality from sensors and IoT put throughout the system. The DT would enable municipal officials to monitor the functioning of the water distribution system, identify possible problems or leaks, optimise water use, and simulate scenarios to increase efficiency. By adjusting or

applying predictive analytics in the DT, such as adjusting valve settings or running simulations for demand fluctuations, corresponding actions in the physical water distribution system can be executed to optimise its operation and ensure a reliable water supply to the city.

Capabilities

Based on its capabilities, a DT may also be employed in a variety of planning future scenarios, getting insights of physical space and make informed decisions or modifications to the future-oriented policies (Batty, 2018; Deng et al., 2021; White et al., 2021). Due to the global data economy trend, the governments of China, Singapore, United States, and the United Kingdom formed top-down national DT working groups throughout the previous decade to introduce new attractive dynamics to their economies (WEF, 2022). Singapore, for example, launched Smart Nation 2025 in 2015, while the United Kingdom launched the National Digital Twin Programme in 2017, and possibly the most extensive research on DT development capabilities stemmed from this working group. The UK Government and the University of Cambridge collaborated on the Centre for Digital Built Britain (CDBB) as part of the UK's National Digital Twin Programme. Throughout project lifetime between 2017 and 2022, it established strong and viable recommendations for DTs. One of the important studies produced by the CDBB's Digital Twin Hub working group highlighted that DTs may be utilised for a variety of reasons, and the amount of sophistication necessary depends on what you need the DT for.

Table *6* shows an outline of the levels of DT capabilities in the context of smart cities and smart mobility exemplifications are provided.

Table 6. Digital twin capabilities in the context of smart cities and smart mobility exemplification with possible enabling technologies (Modified from CDBB, 2021; Eleftheriou & Anagnostopoulos, 2022; Lu et al., 2019; Qi et al., 2021)

Capability	Description	Example

Descriptive:	The descriptive capacity is concerned with gathering and visualising data to comprehend what is going on in a smart city. It entails duties such as design and construction data transfer, information validation, data stream management and security, and dynamic data aggregation. Interoperability, data quality, standards, format consistency, and update frequency are all factors to consider.	To comprehend present congestion patterns, real-time data on traffic flow in a digital smart mobility dimension is collected.
Informative	In a smart city, the informative capacity is gaining insights by combining and analysing data. It seeks to provide a solution to the issue of why particular events or situations occur. This capacity is based on cutting-edge digital data analytics techniques. Considerations include data quality and completeness, especially when merging various datasets, data consistency, and guaranteeing trust and legal repercussions connected to data ownership and provenance.	Analysing historical data on traffic patterns, weather conditions, and public transportation schedules to identify the causes of congestion and delays in a specific area of a smart city.
Predictive	In a smart city, the predictive capability relies on real-time monitoring and prediction. It makes use of data science and machine learning to anticipate future events and results. Considerations from earlier phases apply, but new considerations include the appropriateness of predictive approaches for the specific use case and cultural acceptance of using predictive analytics.	Using historical traffic data and machine learning algorithms to predict (forecasting) traffic congestion patterns during peak commuting hours, enabling proactive traffic management in smart mobility.
Prescriptive	In a smart city, the prescriptive capacity extends beyond prediction to recommend interventions and actions. To identify what actions should be made, predictive simulation, optimisation, and AI-based learning are used. Addressing bias in datasets, performing "what if" scenarios and assessing results, and identifying ownership of findings when private algorithms are employed are all factors to consider.	Utilizing predictive simulation, running what-if scenarios, and optimization algorithms to provide personalized recommendations for optimal routes and transportation modes in smart mobility.

Cognitive	High-level matrix concept. In a smart city, cognitive capacity allows autonomous actions and interventions within defined limitations. It entails predicting decisions, exploiting massive datasets for learning, and using robotic process automation and business process management to operationalize data. Corrective steps, such as raising flood barriers or diverting traffic, can be automated based on predictions. Considerations include ensuring scalability logic is followed, efficiently blending people, processes, and technology, and managing data in an operational built environment.	Smart mobility IoT sensors gather real-time information on light, weather, and pedestrians. Data analytics and machine learning are used to optimise lighting. An automated DT control system uses edge computing to autonomously make real-time modifications.

In the same vein, both research institutions and academic sources have met in 5-phases on the capabilities of DTs to the extent of maturity level spectrum and understanding level of its CPSs (See, **Table 7**). Although the system complexity and the blending enabling technologies of each stage increases, it is not linear or consecutive (Global Data, 2020).

Table 7 Stages of digital twins: Maturity levels and understanding perspectives (Derived from Deren et al., 2021, 2; Global Data, 2020, 13).

Digital Twin Maturity Level Spectrum	Understanding Level of CPSs at Maturity Level
Stage 1: 2D map/system or 3D model (e.g., object-based, with no metadata or BIM) or design/asset optimization and coordination	a. Digital twins are 3D models. b. Digital twins are copies of physical entities. c. Digital twins are virtual prototypes.
Stage 2: Connect model to persistent (static) data, metadata, and BIM (e.g., documents, drawings, asset management systems) or 4D/5D simulation or design/asset management or BIM Stage 2	a. Digital twins are data/big data. b. Digital twins are PLM (Product Lifecycle Management). c. Digital twins are digital thread.
Stage 3: Enrich with real-time data (e.g., from IoT, sensors) or operational efficiency	a. Digital twins are physical union platform. b. Digital twins are industrial Internet platforms
Stage 4: Two-way data integration and interaction or remote and immersive operations or control the physical from the digital	a. Digital twins are simulation. b. Digital twins are virtual verification. c. Digital twins are visualization.
Stage 5: Autonomous operations and maintenance or complete autonomous operations and maintenance	a. Digital twins are pure digital representation or virtual entities. b. Digital twins are irrelevant to entities

As depicted in table, DTs exist at varying degrees of development and capability along a maturity level spectrum. At the first stage, *descriptive digital twins* consist of 2D maps or 3D models without metadata or BIM, with an emphasis on design optimisation and coordination. At stage 2, an *informative digital twin* model connects to static unidirectional data, metadata, and BIM, allowing for 4D/5D simulations, design and asset management, and operational efficiency. Moving further, in stage 3, the *predictive digital twin* is articulated by real-time data from IoT and sensors, enhancing operational insights. Any data acquired from observing a physical entity may be recovered from its DT.

Predictive DTs, in theory, may be of great aid in dealing with the four types of system behaviour; we can be assured that we could acquire the *predicted desirable*, remove the *predictable undesirable*, and mitigate the *unpredictable undesirable*, but having *unpredictable desirable* indicates that we do not completely understand our CPS (Grieves & Vickers, 2017, 90). The next phase, stage 4, *prescriptive DT*, entails bidirectional data integration, remote and immersive operations, and even control of the physical entity from the DT. Finally, *cognitive DTs* enable fully autonomous operations and maintenance at the maximum degree of maturity. At this stage, DTs may be thought of as platforms for fused CPS, pure digital representations, or ideal matrix.

2.3.2 Conceptual Backgrounds of Digital Twins in Smart Cities

When examining the DT practices in smart cities, the most noticeable phenomenon in the literature is the variable terminological usages of “urban”, “district-scale”, “city”, “smart city”. Examples of this can be found in the studies of "district-scale urban digital twins" (Alva et al., 2022), "Urban Digital Twins" (Ferré-Bigorra et al., 2022; Raes et al., 2021), "City-scale Digital Twins" (Nochta et al., 2021), "Digital Twin City" (Deng et al., 2021; Deren et al., 2021), which essentially ponder on DT application practices in the city domain. The general opinion is that these terminological terms can be seen as reducing the existing complexity of city systems. For example, Alva et al. (2022, 5) drew attention to this issue in their study on the use of DTs in cities and elucidates the reason as follows: "A district is an administrative division of a country or town with fixed borders and is used for official purposes. However, the term district is used differently in different contexts and countries, generally as wards or sub-cities that are subdivisions of a municipality or 'prefecture-level city'”. Although the terms used in studies focusing on city-scale DT implementation approaches vary, there is a fact that the DTs that are tried to be implemented at the city level share common technical, use case and benefit characteristics in many ways in cities (Deng et al., 2021).

“DTs in smart cities should be treated differently and be considered as cyber-physical ‘systems of systems’, due to the vastly different system size, complexity and requirements, when compared to other recent applications of DTs.” (Mylonas et al. 2021, 143222). Given the systemic complexity of cities discussed in previous sections, the application approaches, or goals of DTs to SC systems varied significantly. As Nochta et al. (2021) and Qi et al. (2021) note, the technological and architectural infrastructure characteristics of physical objects in both industrial and manufacturing DT applications are so distinctive that, when considered as "living systems" or even "organisms" such as cities (Mylonas et al., 2021), the SCDT requirements are so diverse. Likewise, the techno-centric approach revealed by the application research of DTs in manufacture settings exhibits an approach that ignores human factors, the most important part of urban dynamics, which limits the applicability of DTs in smart cities (Lehtola et al., 2022).

In contrast to industrial CPSs, where a “physical object” represents a “product” or systemic process and frequently raises security grounds like intellectual property rights, the integration of “human agency” as “physical entity” into the SCDT system brings issues of privacy, security, ethical considerations, and trust issues (Fuller et al., 2020). This is because in the SCDT systems-thinking, humans are both the data source and the data consumer.

SCDTs are a challenging endeavour that encode physical city system parts and their interactions. Smart cities increasingly use contemporary ICTs to make cognizant decisions that encourage resilience and improve the lives of residents. Keeping in mind that smart cities as socio-technical systems with differing regime actors such as users, policymakers, societal groups, industry, they are sharing similar goals, values, and problem-solving agendas in their context (Geels, 2004). Thus, the sustainable transition necessitates the creation of a common knowledge base supported by shared rich vocabularies that can handle and govern the variety and volume of data being gathered in cities.

Petrova-Antonova et al. (2021, 387) claimed that issues with data silos and a lack of semantic interoperability in SCDT modelling need the use of upper-level ontologies. For instance, "object" denotes "a physical entity", “entity” is used to describe the “a particular thing" and the "thing" might be a structure, a person, a smart mobility system, or the entire city (Petrova-Antonova et al., 2021). Yet, "object" in industrial terminology denotes a product or manufacturing process (Grieves & Vickers, 2017). This is crucial for the development of common standards and a problem-solving methodology among regime actors. In other words, systemic transformation will not succeed if actors, who are a part of the socio-technical system, conceptualise the human factor by disregarding its emotional state (Raes et al., 2021) in SCDT solutions as a product or object as in industrial solutions.

Recent empirical and theoretical studies have given compelling cases of the needs of cities for which DTs can be integrated in smart cities in relation to external factors currently they are exposed or might be subjected in the future (See, **Table 8**).

Table 8. Smart City Digital Twin Use case examples and explanations (Alva et al., 2022; Deren et al., 2021)

Use Case	Explanation
City-Level Forecasting	Smart cities can use DTs as a tool to address the challenges of rapid urbanisation, such as asset assignment and utilisation, resource preparation and maintenance, and waste management. DTs can provide independent guidance aimed at communicating outcomes at the district or municipal level. Urban management, planning, and associated services promote the ability to make well-informed decisions.
Emergency Planning	Designing and planning quick fixes or escape plans for catastrophic disasters is the goal of DTs for Emergency Planning. Incidents that might entail natural disasters, dangers to healthcare, security risks, or other risky circumstances for communities.
Operational Optimisation	For a variety of urban systems and resources, including urban transportation, energy, environment, communication, buildings, and infrastructure, performance management of operations can be improved by DTs for operational optimisation.

Participatory Planning	As instruments for storing, accessing, comparing, and analysing various sorts of data as well as distributed decision-making through participatory procedures, urban planners and administrators can use DT platforms. Through several enabling technologies including IoT, VR, AR, machine learning, and natural language processing, the CPSs of cities are intertwined for participatory future strategies.
Policy Development	Policymakers should be equipped with the instruments necessary to carry out trustworthy, timely studies and complete scenarios of urban logistics considering the impending technical, business model, and spatial-temporal shifts that innovations will bring. Informed, efficient, and participatory planning procedures may be encouraged with the use of DTs, which can then be used to forecast behaviour and response to both the implementation of policy measures and structural changes.
Scenario Modelling – What - IF Analysis	Through the accurate depiction of a real-world problem for virtual testing, DTs for scenario modelling can explore design alternatives and what-if analysis. Virtual scenario modelling experiments in DTs can produce the extensive datasets and statistical power to examine alternative scenarios for high-dimensional traffic, notably safety evaluation and "stress testing" of autonomous driving features.
Smart Grid DT Services	It is a simulation process involving several physical quantities, temporal and geographical scales, and probabilities. It fully utilises the power system's physical model, online measurement data, and historical operation data. It maps out the complete life cycle process of the smart grid in virtual space.
Smart City Traffic Brain	Based on real-time traffic data flow, DT realises traffic big data management. It can create an algorithm for evaluating congestion indexes that incorporates historical congestion data, traffic data, vehicle speed data, and other information to realise informed functions.
Smart City Public Epidemic Service	The patient's spatiotemporal data can be generated by combining the hospital's given patient information with the patient's spatiotemporal trajectory data. The DT can identify epidemic outbreaks and persons near one other by using artificial intelligence (AI) and machine learning (ML) for spatiotemporal proximity analysis. The findings can be promptly transmitted to the component of the response system.

Flood Monitoring and Flood Situation Services	The smart city flood monitoring system based on DTs has three major components: real-time flood data collecting utilising IoT technology, flood knowledge mapping, and flood service applications. The system collects flood-related data from a variety of sources, including urban meteorological stations and ground sensors, to monitor river water status, rainfall, and human and vehicle movements. It also makes use of satellite remote sensing technologies to monitor changes in water volume and level in rivers and reservoirs across wide areas.

For instance, in the study by Alva et al. (2022) on the use cases of city-scale DT applications on SC modelling, managing and analysing buildings, transport, energy, water, utilities, and infrastructures, use case categories were discovered. Forecasting at the city level, disaster preparation, operational optimisation, participative planning, formulating policies, and scenario modelling, to name a few (Ibid). Similarly, Deren et al.'s (2021) research focuses primary uses of DTs in smart cities. These includes, smart grid DT services, SC traffic brain, SC public epidemic services, flood monitoring and flood situation services. Mylonas et al.'s (2021) survey research is another extensive investigation. Although the application areas, such as energy, urban planning, and traffic monitoring, share certain similarities, the circular economy, sustainability, resilience, and health are highlighted in Mylonas et al.'s (2021) study on DTs in smart cities.

To enable multiple degrees of fidelity city needs, a consistent and holistic DT of a SC is vital. Lehtola et al. (2022, 2), for instance, argue that DTs are not just technical infrastructure or computer modelling in cities, but rather their importance in organising the city's daily services and making informed decisions. They also emphasise that DTs of urban systems and services must meet four main requirements.

- The city's primary stresses should be met by the DT.
- DT should also support low-fidelity elements at the local level in addition to high-fidelity priorities.
- Given that the city is continually undergoing systemic changes from second to second, thus, real-time, and uninterrupted bidirectional data flow ought to be given high importance.
- There should be an attempt to establish citizen-oriented DTs, which means that the human aspect should be included into DTs in future-oriented decision-making systems (Raes et al., 2021; White et al., 2021).

Albeit abundance of distinct attempts, there is a lack of holistic and unified SCDT frameworks and models in the context of cyber-physical systems-thinking. Deng et al. (2021, 132), for example, suggest DT city framework covers three primary levels. While one of these levels involves infrastructure-enabling technologies, the other two layers focus on the city brain and applications. When the framework is examined, however, the proportions of the SC are not clearly defined, nor is the feature of the data flow that comprises the DT described. Similarly, White et al.'s (2021, 3) six-layered DT SC model, while realistic and elegantly simplified for comprehension of SCDT interoperability, has major fundamental flaws. In the third layer, for example, mobility is defined as people's movement in their daily lives. This layer, on the other hand, portrays a system, namely the entire city. Mobility, environmental conditions, stakeholder governance, interactions of people, and services that influence living standards are only a few of them systematically managing people's everyday lives in cities. Another example is the work of Mylonas et al. (2021, 143229). Their model, which offers a high-level perspective on city-scale DTs, includes physical and virtual spaces as well as security, but still shows a distant character in the SC systems-thinking.

Considering the studies in the recent literature in this research and these three examples in addition to the requirements mentioned above, the call for a holistic and unified SCDT framework reinforces the argument for the lack of a holistic and unified SCDT framework (Dignan, 2020; Lehtola et al., 2022; Raes et al., 2021). Every endeavour has been unique, and their efficacy is heavily reliant on their application in the local settings. Yet, what smart city DT cyber-physical systems have in common is that it is the city's socio-technical systems as an entity of physical space is represented in virtual space (Fuller et al., 2020).

"Smart City Digital Twin Cyber-Physical Systems Thinking" was the respond to the calls (See, **Figure 5**). This call must be answered to make sense for the reader to grasp fundamental logic of IPRM which was explained in more details in Section 3. The primary component of IPRM layers, "Key Enablers," connects the physical environment to the 4. Layer - Smart City in Cyberspace in Figure 5. This link enables the desired smart city application, eventually, the smart city digital twin application in 5. Virtual Layer. Figure 5 depicts a "Cyber-Physical Systems-Thinking of Smart City Digital Twins".

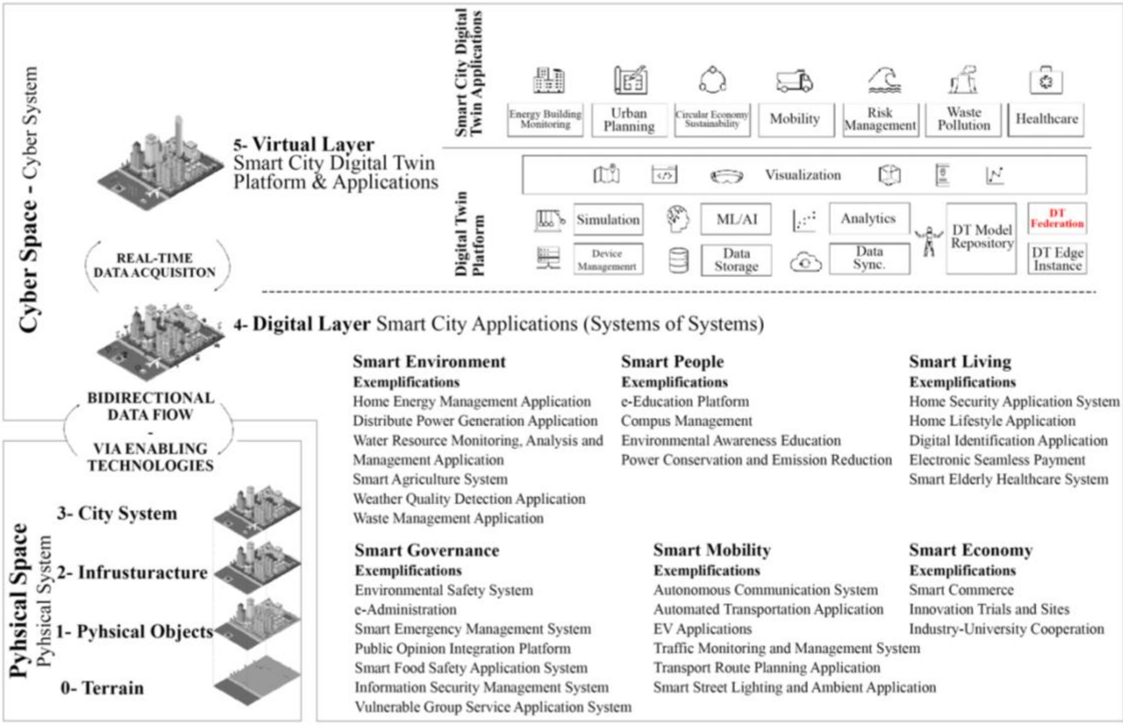

Figure 5. Smart City Digital Twins Cyber-Physical Systems Thinking (Modified from; Lu et al., 2019; Mylonas et al., 2021; White et al., 2021).

Physical space constitutes four layers. The basic one, **Layer 0 - Terrain** depicts the city's basic geographical structure. **Layer 1** portrays the physical entities found in the city, such as buildings, people, and automobiles. In **Layer 2, i**nfrastructures, surrounds, institutional, and organisational structures are all represented. **Layer 3** depicts city's system of systems, namely the entire city. Mobility, environmental conditions, stakeholder governance, human connections, and services that impact living standards are only a few of the factors that systematically manage people's daily lives in cities. The cyber space, which has bidirectional data connections with physical space via enabling technologies, comprises the **Layer 4.** - Digital Layer, which represents SC applications in various dimensions – mobility, environment, governance, economy, people and living. The **Layer 5** contains SCDT applications fed by real-time data flow from **Layer 4**.

An exemplification of systems-thinking based on the physical space traffic system of a city in the context of the smart mobility socio-technical system transition in the cyber space. Due to traffic congestion caused by the city's rapid population and urbanization growth, the municipal administration wishes to shift from the old system to the smart mobility traffic system. They begin by developing a shared policy vision with the technological infrastructure needs that will enable this transition and the associated solution partners, i.e., socio-technical regime players. While this may create new windows of opportunities for niche developments, it also might create some fragments in the smart mobility regime.

As a result, with novelties in smart traffic system via GIS, and IoT sensor technology integration with GPS, smart traffic monitoring and management system align to traffic system mainstream. Instead of the city's previous traffic system, SC mobility applications such as traffic monitoring and management in a SC mobility dimension come to life in the digital layer. The most essential aspect is that the real-time data gathered from this digital layer may also be utilized the virtual layer SC mobility DT application using technologies such as ML, AI, and Data Analytics. The user of the SCDT platform can mitigate the physical traffic congestion (for example after a big concert in city) based on the outcomes of the insights, simulations, and what-if analysis derived from DT application. Ideally, cognitive SCDTs should do this autonomously with its characteristics of "self-perception, self-decision, self-organisation, self-execution, and self-adaptation" (Deng et al., 2021, 131).

Smart City Digital Twin Cyber-Physical Systems-Thinking, represented in Figure 5, was inspired by the three primary frameworks (Lu et al., 2019; Mylonas et al., 2021; White et al., 2021), and offers a unified and holistic framework. This effort was extremely crucial for the natural flow of this study in embedding the core reasoning of IPRM to the reader. Furthermore, this attempt on a unified framework meets the Lehtola et al.'s (2022, 2) four primary requirements and helps to minimise the limitations of the three framework components to some extent.

2.3.3 Smart City Digital Twin Opportunities

Based on the materials studied thus far, DTs, like their industrial ancestors, provide multiple opportunities for the operation of SC systems. DTs are gaining popularity as transformative tools in urban planning and SC development. These virtual representations of physical city systems, complete with real-time bidirectional data and strong simulation capabilities via AI, ML, Cloud Computing and IoTs, assist public administrations, individuals, and businesses in a variety of ways.

The multiple benefits of SCDTs, as articulated by various scholars in pieces of literature, demonstrate how SCDTs promote better-informed decision-making and stimulate public involvement and participation. They act as strategic planning sandboxes, promote long-term visioning and anticipation, and enable real-time monitoring and efficiency in daily city operations. Through an analysis of their uses, they contribute to the creation of future-oriented policies for complicated urban environments.

DTs support participatory future-oriented informed decision-making by attracting the engagement of individuals in smart cities. Real-time data and information, for example, can foster community involvement and participation by strengthening people's digital literacy and culture (Kaluarachchi, 2022). Facilitating open data usage enhances citizen involvement and engagement in urban planning (White et al., 2021). As a result, DTs enable authorities to make informed decisions regarding future city development and operation (Ferré-Bigorra et al., 2022). Furthermore, governments by utilising top-down approaches or fusing it with bottom-up initiatives urge local governments to anticipate, respond, and plan future scenarios using real-time data, resulting in future environmental, social, and economic advantages (Kaluarachchi, 2022). As Nochta et al. (2021) remind us that each SCDTs should consider its city dynamics and characteristics, a hybrid approach can be embraced in which distinct activities can be undertaken towards a complementary shared future vision. A hybrid method that mixes the government's top-down national carbon-zero vision against climate change and specific socio-technical system regime modifications with bottom-up SC transformation with its own dynamics is an example of a hybrid approach. City officials who can link their own dynamics with citizen-centric SCDT and governments with top-down – good for all – applications could leverage on these advantages and promote future-oriented informed decision-making processes in cities and countries.

As strategic planning testbeds, unified and holistic DT design promotes sustainable socio-technical transformation and growth. For example, Ferré-Bigorra et al. (2022) underline that as strategic planning sandboxes of unified DTs, public and private efforts may collaborate and test possible outcomes of their joint initiatives in advance. On the other hand, the previously mentioned system dynamics of smart cities should not only be driven by the collaborative efforts of private and public initiatives but should also consider issues such as industry, science and research centres, policies, users, and market dynamics that comprise the SC system's socio-technical regime. SC system transformations are conceivable, if all system actors share common values and benefits in regime and contribute to the defined vision. DTs save money and time while boosting planning efforts, which is an advantage shared by other domains (Lehtola et al., 2022). DTs can be utilised to evaluate various scenarios and intuit ideal options as living testbeds with big data analysis and technology tools (Fuller et al., 2020). Through a unified and holistic DT design that incorporates all players who are likely to contribute to socio-technical transformation, both strategic planning and sustainable growth may be realised.

DTs add value by enabling not just real-time remote monitoring and control, but also greater socio-technical efficiency in smart cities (Rasheed et al., 2020). Cities are focusing their efforts to smarten their physical system dynamic with ICTs on improving informed decision-making, enhancing citizens' well-being, reducing operational costs, disaster management or mitigation, and developing sustainable growth with new business models by integrating all the benefits of the data economy into system dynamics in today's conditions (Mylonas et al., 2021). In this context, DTs can simulate possible phenomena like floods and pandemics, as well as promote integrated strategies including all system stakeholders (White et al., 2021). Finally, they could shape the future of their cities collaboratively through participatory future scenario planning that includes all stakeholders, including citizens (Lehtola et al., 2022). Finally, DTs can not only strengthen cities' resilience systems technologically but also allow participatory long-term SC socio-technical shifts in which visionary values are embraced and shared within their regimes.

Overall, DTs provide a variety of benefits in smart cities, ranging from enhanced decision-making and planning to citizen participation, cost and time efficiency, and scenario development facilitation. They are effective tools for cities and governments to use in adapting and being resilient to landscape drivers such as urbanisation challenges and creating sustainable, creative, and well-functioning urban environments for citizens.

2.3.4 Smart City Digital Twin Challenges

As cities face unprecedented challenges because of rising landscape challenges such as climate change, demographic changes and urbanisation, these cyber-physical systems prove to be vital tools for creating the resilient cities of the future, but those advantages also come with broad distinct challenges in feasibility, technical infrastructure, skills and competences, data governance and policy articulation within socio-technical city systems.

Feasibility and Scalability

There are several technological impediments that indicate unresolved issues in SCDT initiatives (Barricelli et al., 2019). The most significant of them is the gap between technology and market maturity. Lu et al., (2019) conducted comprehensive study including 80 SC cases around the world, their analysis reveals that sensor and integration technologies that can pave the way for DT applications in smart cities will reach maturity in the next three years, but almost none of these technologies have matured in the market expectation analysis. Also, according to Ferré-Bigorra et al. (2022) the mainstream of SCDT applications is either prototypes or periodic projects in the development phase undergoing feasibility testings. It is due to the substantial cost of implementing and maintaining certain technologies (Fuller et al., 2020).

Scalability of prototyped DT practises is another critical challenge. According to Mylonas et al. (2021), this might be due to a lack of adequate existing infrastructure or network mapping documents, or simply an inability to update the present system without re-installing everything due to vendor lock-ins. Vendor lock-in concerns are also addressed in scalability difficulties for DTs in SC projects (Lehtola et al., 2022). According to Barricelli et al. (2019) and Ferré-Bigorra et al. (2022), the high expenses make SCDT applications available mainly to major corporations with the appropriate cash and human resources. But one of the current problems is corporate business models approaches are broadly customer based and disregarding human factor in their DT solutions. There are other sectoral hurdles here as well. According to Dignan (2020), corporations are failing to dominate the smart cities market because they continue to rely on old business models with short return on investment (ROI) expectations and continue to focus on patent point solutions. As a result, the transformation process may be stalled since they are competing for the greatest value offer to get a competitive edge in the market. The competitive advantage might manifest itself as a company's hidden "Intellectual Property Rights" or patents and algorithms underlying AI, ML, and IoT, which could force other businesses out of the game. For example, Lehtola et al. (2022) focuses on back-end technical concerns, particularly cartographic visualisation issues associated with DTs in smart cities to the extent of interoperability, such as technical codes for symbolization, graphics, and interface usability in 3D simulations or virtual replications in DTs must be addressed.

When we consider cities with small amount of budget for SCDT developments, many of them are funded by Horizon 2020 one of the European Union - financial support initiatives (Ferré-Bigorra et al., 2022). International financial and governmental organisations such as the World Bank and the EU are making efforts, but not with a coordinated approach (Dignan, 2020). The European Commission, for example, showcases funded SC initiatives on the "EC - Smart Cities Marketplace". It is a platform for distribution of project deliverables and know-how in other EU countries. Although these and similar platforms provide several benefits, their negative consequences on scalability should not be overlooked. In addition to Qi et al.'s (2021) notice that DTs are closely related to specific objects and entities in physical space, Lehtola et al. (2022) and Nochta et al. (2021) emphasise that, while DTs share technical similarities, it is critical for scaling that they reflect specific characteristics such as governance structure, processes, and city needs at the local scale.

Likewise, Kozlowski & Suwar (2021) argue that urban authorities and communities worldwide show interest in smart cities, but the diverse implementation of smart solutions stems from cultural, social, political, economic factors, and available resources. While European cities prioritize green initiatives and addressing social issues such as aging, and Polish cities tend to adopt proven smart solutions from other European cities (Kozlowski & Suwar, 2021). So, no solid evidence exists that a SCDT prototype funded for feasibility in Poland can be deployed in a Finnish city. In a sense, such dispersed DT initiatives, each aiming to solve a specific urban problem in a specific country, lead to a lack of consensus on a unified and holistic generic DT model and scalable infrastructure perspectives (Fuller et al., 2020). Thus, it seems that scalability issues will continue to be a major challenge in the development of SCDTs.

Technical Skills & Infrastructure

Cities have undergone systemic shifts with constant ICT integrations throughout their history. However, Covid-19, as a specific shock or disruptive change at the landscape level experienced recently, has also promoted digitalization in SC transformation (Boulanger, 2022), and the reality that DT applications become a must for smart cities (Dignan, 2020). Cities have clearly been pushed to get intimately acquainted with technical enablers such as Blockchain, VR, AI, and Deep Learning, and IoT, as well as conceptually recognise these technology infrastructures. As DTs are technically sophisticated, skilled professionals are necessary to create, implement, and maintain them (Ferré-Bigorra et al., 2022; Kaluarachchi, 2022). Not only that, but this pressuring driver for cities has exposed several technological competence concerns. First, cities lack skilled data management, processing and analysis specialists (Kaluarachchi, 2022; Mylonas et al., 2021); second, current DT approaches emphasise only technology, ignoring the essential needs of cities and citizens, public interests, and understanding of non-profit as notion of public administration (Lv et al., 2022; Nochta et al., 2021); and finally, citizens must be equipped adequate digital skills in order to benefit from SCDT applications and its services (Mylonas et al., 2021).

The added value of ever-advancing technology innovations in every area has made it critical for global, regional, and national upskilling efforts that follow digitalization and digital economy trends. In addition to the very strict and always up-to-date new studies of supranational global organisations, such as the United Nations and the European Union, states that states want to participate in the digital skills race and close the skills gap to conduct accurate upskilling mechanism and incentives within their own borders. In general terms, both the European Union's Digital Skills policies (EC - Digital Skills: Shaping Europe’s Digital Future) and the Finnish Ministry of Economic Affairs and Employment's report on an ecosystem-based Digitalisation Academy Model "Talent Retention and the Development of Digital Skills" (Niemi et al., 2021) can be some of the examples.

However, at a more local level, it seems that, two approaches among the dozens of studies that aim to guide cities’ capability and upskilling objectives based on SCDT transformations can append each other and shed light on required skills and competencies of those professionals in cities. The first one is the "Smart City Operation Brain Management Architecture," (See, **Figure 6**) which Deren et al. (2021) provide a general perspective on the SCDT architecture, and the second is the “Skills and Competency Framework”, (See, **Appendix 1 CDBB’s Skills and Competency Framework: Professional Digital Twin talents, their** essential tasks and required skills.) which is the result of the 5-year work of the Centre for Digital Built Britain's National Digital Twin Programme. It frames the essential tasks and skills of the necessary experts and professional talents that can sustain this DT architecture.

SMART CITY OPERATION CENTRE (SCOC)

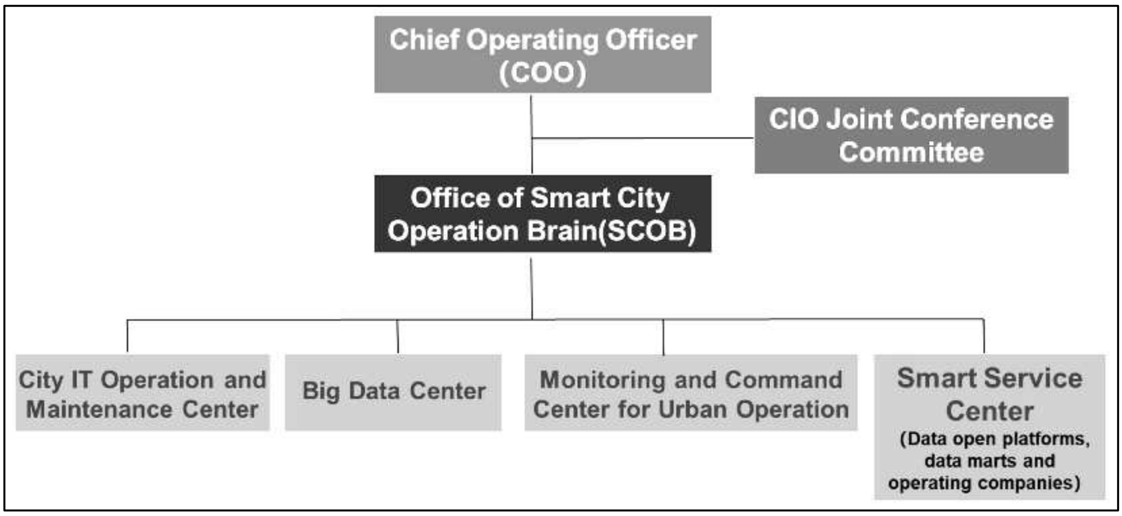

Figure 6. Smart city operation brain management architecture based on digital twin (Deren et al. 2021, 3).

Figure 6. illustrates the full management aspect of Smart City Operation Centre – SCOC based on SCDTs. Smart City Operation Brain (SCOB)'s primary tasks involve taking part in and analysing high-level municipal design and planning (Deren et al. 2021). It strives to produce applicable rules and standards, as well as combine them with urban information resources, by assessing the growth of IT in various industries. It intends to support the construction of a system for socially engaged big data open-apps and services via tracking city operations and cooperating across departments.

The major problem in this modelling is lack of explicit description on what roles and skills "city officials" should have for these blocks to operate and for an effective and sustainable style of DT functioning. In this regard, Centre for Digital Built Britain's National Digital Twin Programme’s Skills and Competency Framework (2021) might fill this gap (See, **Appendix 1** CDBB’s Skills and Competency Framework: Professional Digital Twin talents, their essential tasks and required skills.). It may assist Finnish smart cities’ DT transformation by identifying and filling any skill shortages. It also offers a clear learning route for those involved in the creation and deployment of DTs. The “Skills and Competency Framework”, is critical in qualifying organizations to build local SCDTs by which it can step Finland towards establishing the Finland’s National Digital Twin Programme (or even towards Digital Twin Federation). Failure to understand these skill requirements may result in organisations hiring insufficiently skilled personnel for their DT initiatives, resulting in a loss of confidence, poorly designed twins lacking interoperability and connectivity, and unsuccessful DT projects, ultimately resulting in negative economic consequences for these organisations.

Aside from its skill and job complementarity to the SCOB's blocks, Skills and Competency Framework (2021) distinguishes three primary aspects. The first is the tasks necessary for national leadership of local DTs, where all SCDTs in the country acknowledge each other as an ideal model and follow the concept of an interoperable system. Second, at the national level, industry leaders, sector regulators, and policymakers, as well as at the local level (organizational), user researchers and data consumers address socio-technical systems thinking. If the socio-technical regimes discussed in depth with MLP are revisited, it will be noted that regimes such as industry, policy, user, and market are dependent on the shared values, vision, and perceptions necessary for SCDT socio-technical changes. As a result, these roles and skills might be referred to as the essential socio-technical skills and roles for socio-technical change in smart city system of systems. In this sense thirdly, this framework provides a unique hybrid guide tackling technical skill challenges with enabler roles and their tasks in both local and national levels. Overall, collaborative socio-technical design is critical for bridging communication barriers between actors (Barricelli et al., 2019). The lack of top-level planning, on the other hand, has resulted in fragmented SCDT development (Lv et al., 2022). Thus, it is critical to do top-level planning based on the characteristics and needs of each city to build SCDTs (Deren et al., 2021).

Data Governance

SCDT applications confront a variety of data governance difficulties, such as establishing trust with stakeholders, resolving ethical and privacy concerns, and managing data quality and ownership.

Recent studies show that trust-building and stakeholder involvement are critical success elements in SCDT applications (Hämäläinen, 2021; Raes et al., 2021; White et al., 2021). For instance, Barricelli et al. (2019) raise ethical, cyber-security, and privacy concerns, emphasising the significance of resolving difficulties resulting from data exchange across diverse sources and actors in DT applications. Fuller et al. (2020) and Mylonas et al. (2021) add the difficulty of growing monitoring and regulation of enabling technologies such as AI and ML, with a particular emphasis on safeguarding user data, as issued by the General Data Protection Regulation (GDPR). Moreover, Hämäläinen (2021) and Raes et al. (2021) claims that technical measures alone will not be sufficient to build trust; instead, active participation and communication among stakeholders is must and Quadruple Helix collaboration would be useful framework for joint SCDT conceptualization and data management addressing challenges in local context.

Innovative incentives for third-party participation, as well as the complexity of various data governance frameworks, are critical in shaping future of the SCDT. Lehtola et al. (2022) address cyber-security challenges raised by third-party engagement in DTs, particularly when these twins must be accessible and updatable by other actors. They continue as, innovative incentives must be implemented to promote third-party sensor data inputs. Meanwhile, Micheli et al. (2020) highlight the availability of a variety of data governance solutions, such as data sharing pools, and personal data sovereignty. These models incorporate a variety of parties, including small enterprises, government agencies, and civil society, which adds to the complexity of data governance strategies. Moreover, Mylonas et al. (2021) emphasises the importance of data availability and quality in real-world DT deployments as the problem of data ownership becomes more complicated, particularly regarding urban datasets.

Addressing algorithmic bias, identifying DT kinds, and rectifying uneven measurement location distribution is critical for adequate urban development amid the revolutionary potential of SCDTs. For example, (Barricelli et al., 2019) encourages for distinguishing two sorts of DTs representing entities of physical space: those related to things (DTObject) and those tied to humans (DTHuman). The notion of a DT of human or citizen has made its way into the literature. Gartner (2022)'s "Hype Cycle for Digital Government Service" includes “DT of a Citizen" which is predicted to mature in 5-10 years. Also, the blueprint for Citizen DT proposed by Kopponen et al. (Citizen Digital Twin) is notable for their numerous principles, concepts, operating model, and design recommendations. They claim that "it will help service and data providers, both public and private, to develop a common understanding of the role and possibilities of a citizen's controlled personal DT of themselves - a Citizen Digital Twin (CDT) - for creating people-centric DT solutions" (Ibid, 1). Other challenge is raised by Kordzadeh & Ghasemaghaei (2022), they emphasise the critical issue of algorithmic bias, emphasising that data-driven decision-making can result in socially biased decisions, sustaining workplace and societal inequality. In addition to that, Ferré-Bigorra et al. (2022) also draws attention to the uneven distribution of measurement crowd-source locations within these DT applications, which favours heavily inhabited regions and may result in unbalanced representation and decision-making processes.

To sum, concentrating these challenges is critical for realising the full potential of SCDTs while also guaranteeing equity. Tackling data governance issues in SCDT applications necessitates coordinated efforts. Building confidence, addressing ethical and privacy concerns of citizens, and enforcing sectoral standards are all critical. Adopting data governance approaches complying with national and local context and minimising algorithmic bias are essential for achieving equitable outcomes. Proactive measures stemming from pressure selection criterion, innovation, and stakeholder participation could assist to build transforming and secure SCDTs for a connected and inclusive future.

Policies and Sectoral Challenges

In recent years, the notion of DTs has received a lot of interest, particularly in the context of smart cities and urban management. They have enormous potential for transforming numerous sectors and enhancing policymaking processes. Nonetheless, they created significant challenges in terms of policies and sectoral relevance.

Table 9 summarises policy, and sectoral challenges. In this way, it is expected that the components of the IPRM in the methodology section would be clarified to some extent.

Table 9 Summarised policy and sectoral challenges related to future smart city digital twin initiatives.

Policy Challenges	
Theme	**Explanation**
Short-termism	Short-termism and project-based and/or fund-based periodic DT initiatives deliver a significant obstacle (Raes et al., 2021).
Misconceptions	Divergent definitions, models, designs, and misconceptions have led to confusion and non-scalable implementations (Alva et al., 2022; Fuller et al., 2020).
Upper-level ontology	The upper-level ontology should be a first step towards the deployment of city DTs, addressing issues such as semantic interoperability and data consistency, as well as complexity, volume, and quality (Mylonas et al., 2021; Petrova-Antonova & Ilieva, 2021).

Digital Twin Bureaucracy	Digital Twin Bureaucracy – DTB is fundamentally distinct from e-government and smart government, and restructuring will be necessary for real-time interaction with the physical world (Eom, 2022).
Legal Responsibility	There is also the legal issue of who is responsible if the DT makes a bad judgement in a smart city (Ferré-Bigorra et al., 2022).
National & International Policy Standardization	The importance of national and international standards in addressing difficulties related to data storage, compression, security needs, and data sharing across different geographical locations and entities is emphasised (Rasheed et al., 2020).
Multi-actor communication	To bridge communication barriers among participants, sociotechnical and collaborative design approaches are required (Barricelli et al., 2019).
Socio-technical perspective in policy design	The socio-technical perspective on SCDT development should be emphasised, considering high-level policy goals, local context, and the importance of human and organisational learning (Nochta et al., 2021).
Vertical & Horizontal Interoperability in Local and National Level	There is a lack of vertical and horizontal interoperability between departments, resulting in repetitive expenditures and construction, as well as a greater level of top-level design thinking and political wisdom required to develop an integrated city perception network (Lv et al., 2022; Lu et al., 2019).
Local Context	For conceptualising, creating, and implementing SCDT systems as assemblages reflecting local contextual opportunities and limitations, a socio-technical approach is necessary (Nochta et al., 2021).
Citizen-centricity	An emerging topic in the literature is citizen-centric DTs (Raes et al., 2021; White et al., 2021).
Sectoral Challenges	
Theme	**Explanation**
Scaling Issues	The development of critical technologies, particularly shared open data platforms and Application Programming Interfaces (APIs) no vendor lock-ins, should be prioritised (Lu et al., 2019).
Old Business Models	IT firms have failed to dominate the smart cities market because they are committed to old business models with insufficient return on investment (ROI) and continue to rely on patented point solutions (Dignan, 2020).
Citizens or Consumers	Local public administrations are the primary promoters of urban DTs, and public administrations are the primary consumers of these DTs (Ferré-Bigorra et al., 2022).
High-level systems thinking on city	A city is an open, complex, giant system. There is a lack of scientific, reasonable, and methodical top-level design and planning (Lv et al., 2022).
Local degrees of fidelities	A holistic city DT must support several local degrees of fidelity (Lehtola et al., 2022).

Quadruple Helix Cooperation	Cities should change their strategy to facilitate more dynamic quadruple helix cooperation (working with players other than ICT giants, including academia, start-ups, and citizens), to avoid the danger of vendor lock-in and multinational corporate's domination in smart city development (Hämäläinen, 2021).
Common Feasible Architecture	Higher-level Connected DTs can optimise the performance of organisations and industries across borders, necessitating a common architecture for effective and secure communication across DTs (Raes et al., 2021).
Sectoral Standards	Currently, this lack of standards and interoperability is a significant limitation as only a small number of urban DTs can share data with other cities or organizations (Ferré-Bigorra et al., 2022).

To address these obstacles given by diverging definitions and poor implementations, it is critical to ensure data consistency and quality. Furthermore, standardised frameworks, interoperability, and scalability play an important role among cities and organisations, allowing cooperation and innovation across urban landscapes. Finally, it appears that in all elements of SCDT development, a high-level socio-technical perspective considering local degree of fidelities as well as citizens and city needs should be considered.

In sectoral challenges, the emphasis moves to various components of SCDT initiatives. Sectors are still in the early phases of implementing DTs in smart cities, with Europe emerging as a significant development hub. The engagement of local governments as supporters and consumers of these DTs is noteworthy. However, obstacles such as a lack of ideological understanding, fragmented approaches to SCDT building, and insufficient top-level design, national funding and planning remain. These difficulties necessitate an integrated approach that considers various local degrees and stimulates socio-technical perspectives.

The holistic socio-technical perspective is critical to the effective adoption and integration of DTs in smart cities. Bridging communication barriers within socio-technical regimes and encouraging collaboration among smart city socio-technical system actors – local authorities, academia, corporations, start-ups, citizens, and innovative ICTs can result in equitable and successful SCDT development. In addition, combining social and technological perceptions is critical in designing data-driven solutions and digital tools that are aligned with high-level policy goals and local settings. Thus, MLP emerges as an important analytical tool, emphasising the importance of collaborative settings, context-specific solutions, and effective analysing methods. By integrating these understandings, SC socio-technical system actors will be able to better negotiate the difficulties of DT deployments and realise the full promise of these technologies in creating smarter, more sustainable cities of the future.

2.3.5 Finnish Innovation Policies and Future Trajectories on Smart City Digital Twins

Innovation Policies

Finland's innovation policies have evolved in a very generic direction with disruptive landscape changes and generated windows of opportunities to reach current maturity. Recent reports states that Finland ranks 9th among the 132 economies featured in the Global Innovation Index 2022 (WIPO - Finnish Global Innovation Index, 2022) and in Europe, Finland is an innovation leader with performance at 135.5% of the EU average (European Innovation Scoreboard: Finland, 2022). It is not surprizing that national long-term innovation policy is based on new information and innovation produced by diverse research organisations, companies and other actors in Finnish society and their ability to apply it innovatively and offer added value for the future of Finland. For example, Academy Finland and Finland Technical Research Centre - VTT as researching and continuous anticipation; EU, relevant Finnish ministries, and regional organizations (e.g., Turku Business Region) as funding; and Business Finland as supporting start-ups, businesses with ideas and innovations to take advantage of windows of opportunities.

The most comprehensive and up-to-date study on this subject from a general perspective towards Finnish innovation policies are provided by Sotarauta et al. (2022). According to their study, the evolving innovation policies in Finland can be analysed in four main innovation policy rationales:

Innovation Policy 1.0 (Second World War – 1970): Policies for research and technology-based innovation in Finland. It was founded on linear scientific and technical achievements. The globe had an energy crisis in the 1970s, which slowed global growth.

Transition Period (1980 – 1990s): Finland developed a vibrant technical orientation to increase the technological capability of Finnish businesses, hence reducing reliance on material-based manufacturing and exports. New possibilities and innovative orientations were established. For example, the National Technology Agency (Tekes) was created in 1983, the Science and Technology Council was built in 1987, and the first technology centre in Oulu was established in 1982.

Innovation Policy 2.0 (1990 – 2020): Because of the recession in the early 1990s, Finland chose to change from investment-driven conventional science and technology to innovation-driven policy. Innovation networks improved cooperation between the public and commercial sectors in Finland. Nokia and the ICT cluster's exponential expansion, digitalization, and creative initiatives took advantage of open windows of opportunity. However, the 2008 global financial crisis, the proliferation of Apple and Android, and Nokia's precipitous decline in power, as well as the OECD's assessment of Finnish innovation policy in 2017, called for better coordination and cooperation among policy actors at the national and regional levels, as well as further internationalisation in Finland. (Finnish Ministry of Economic Affairs and Employment; OECD: Reviews of Innovation Policy in Finland, 2017).

Innovation Policy 3.0 (Since 2020s): To enhance effect of innovation policy, corporate and research networks ought to be organised into broader ecosystems. With the Finland National Roadmap for R&D&I (2021), the purpose was to foster ecosystems among regional and industrial players. It shifted the program's innovation policy reasoning to the contracts. New 'The Ecosystem Agreements' agreed in February 2021 between the state and cities to build the world's most functioning experimental and innovative environment by 2030. They are a long-term imaginative cooperative commitment by the state and cities to build competency clusters. As a result, ecosystem agreements that aim to boost the innovative activities of and in cities are increasingly considered key aspects of modern Finnish innovation strategies. (Ecosystem Agreements - Ministry of Economic Affairs and Employment).

Ecosystem Agreements

Finland’s Ecosystem Agreements depend on three main landscape factors. These are climate change, digitalisation, and social wellbeing. Because Ecosystem Agreements states that it is between state and cities to speed up innovations in carbon reduction, digitalisation, and wellbeing (Finnish Ecosystem Agreements). Recalling regime selection pressure (Smith et al., 2005, 1496), it seems that Emergence of alternative 'visions' of the future and the generation of changes in the social landscape caused regime in tension. The agreements, however, are specific to each city area with specific "key strategic contents" as shown in **Table 10** and launched with EUR 5M initial fund from Finnish National Regional Development agencies and further it is expected to be funded by EU (Key Strategic Content of Ecosystem Agreements 2021-2027, 2021). It seems that by Ecosystem Agreements, state embraced endogenous renewal transformation pathway with coordinated response and internal adaptation (See, **Table 2.** Transition Pathway Typologies and Explanations (Adopted from Geels, 2011, 32, 2019, 194; Geels & Schot, 2007, 406–413; Smith et al., 2005, 1499–1502). Endogenous renewals arise among regime members (firms, supply chains, customers, and regulators) by making conscious efforts with vision to find ways of responding to perceived competitive threats.

Table 10. Key strategic content of Ecosystem Agreements: 2021 – 2027 (Derived from Finnish Ecosystem Agreements).

Lappeenranta incl. Imatra: Green electrification **Kuopio:** Health and wellbeing technology, and water expertise **Turku:** Renewing industry and life sciences **Helsinki, Espoo, and Vantaa:** Smart and sustainable urban solutions, wellbeing and health technology, new learning environments and digital solutions of skills development **Oulu:** Digitalisation in the changing urban environment, OuluHealth – Digital wellbeing and health solutions, and sustainable circular economy and clean solutions **Joensuu:** New business in the bioeconomy and circular economy, and photonics business **Lahti:** Carbon-neutral circular economy and sports business **Jyväskylä:** Physical activity, health promotion and wellbeing, and renewing industry	**Vaasa:** Sustainable and smart energy systems **Tampere:** Sustainable industry X (SIX), buildings, energy and infrastructure, and digital health solutions **Seinäjoki:** Sustainable regeneration of the food ecosystem and intelligent regeneration of industry **Mikkeli:** Circular economy of municipal water system **Pori:** Technology metals and circular economy, and automation and robotics **Kokkola:** Battery chemistry, and circular economy and intelligent solutions supporting industry. **Kajaani incl. Sotkamo:** Measurement technology and high-performance computing, artificial intelligence, and data centres **Rovaniemi:** Arctic tourism, and wellbeing services of future and management of distances

The ecosystem agreements support a wide range of projects aimed at fostering innovation and experimental contexts. For example, the European Union co-funded "InnoCities Programme" includes 19 cities and 1 municipality with designated lead topics under ecosystem agreements in Finland (InnoCities Finland). It serves as hub for expertise, research, innovation, and long-term solutions. The agreements also emphasise the development of start-up communities and the establishment of new business ecosystems to stimulate entrepreneurial growth. A focus is to strengthen and update local competence through long-term cooperation between the central government and university cities. Strategic emphasis areas direct development efforts, while tight coordination among enterprises, research institutes, educational institutions, and cities ensures that these policies are successfully implemented.

Finland Digital Compass

Finland's Digital Compass presents the country's long-term strategic roadmap for digitization and data economy transformation. It recognises that the country and the globe are changing because of the continuing decade of digitization and data economy, which affects all sectors of society. The Digital Compass recognises the importance of data and digitalization in everyday life by offering new windows of opportunities while landscape challenges' put pressure and increase the tensions such for skill needs and aging Finnish population. The following are the major objectives and major issues as landscape challenges outlined in the Finland's Digital Compass (Finland's Digital Compass, 2022):

Global Competition: The race to digitalization has heated up, with worldwide rivalry for cutting-edge technology, skills, and experts. To preserve a competitive advantage, Finland must follow a consistent strategy that aligns with the EU's Digital Compass, which was presented in 2021, and the linked EU Digital Decade Programme, and act as a counterforce to global power aspirations and huge firms with vast quantities of data.

Green Transition: While digitization and the data economy provide potential to transition to a more environmentally friendly and resilient circular economy, they also consume energy and resources. Finland must create solutions to quantify and decrease the carbon footprint of the digital economy, positioning itself as a leader in developing green transition solutions.

Geopolitical Issues: Digitalization intersects with foreign policy and alters power dynamics between nations. Large technology corporations' expanding clout in relation to nations, as well as supranational governance that extends beyond borders, are causing geopolitical conflicts. Finland's essential infrastructure, particularly cyber-security and resilience is critical to the country's ability to operate in the face of geopolitical shifts and disruptive changes like as the COVID-19 pandemic.

Main Goals: The Digital Compass centres on four cardinal points, each having prioritised goals for 2030: skills, infrastructure, public services, and business.

Digitally Skilled Population and Workforce: Finland wants to strengthen the skills and competencies of its population and workforce to properly utilise the benefits of digitization. It encompasses media literacy to combat informational impact and promoting a trust-based, open, and democratic society.

Digital Infrastructure: Finland aims to invest in digital infrastructure and vital competences to ensure the smooth operation of society, particularly during times of crisis. This involves guaranteeing the availability and resilience of digital infrastructure, such as energy, transportation, and water resource management networks.

Digital Transformation of Businesses: The Digital Compass seeks to encourage digital transformation of businesses by promoting the use of new technology and business models. This transition boosts productivity, innovation, and competitiveness in both the public and private sectors.

Digital Public Services: The goal is to improve public services through digitization, making them more efficient, accessible, and citizen centric. This involves increasing the digitization of government administration and services.

The challenges and goals mentioned in Finland's Digital Compass have far-reaching ramifications in the context of SCDT socio-technical system change. Cities must handle the worldwide competition for modern technologies and knowledge while actively contributing to the green transition as they embrace the opportunities of digitalization and data-driven solutions. SCDTs are a strong tool for optimising infrastructure, improving services, and encouraging public participation.

Finnish SCDT Trajectories

The Ecosystem Agreements, Finland Digital Compass, and existing Finnish SC strategic goals put more pressure on Finnish cities, increasing system complexity and demonstrating the importance of a holistic socio-technical approach and feasible innovation policy roadmaps for future Finnish SCDT trajectories. Global competitiveness, the green transition, and geopolitical challenges, as described in the Finland Digital Compass, are forcing cities to prioritise creative and sustainable solutions through the Ecosystem Agreements.

The juxtaposition of exogenous landscape changes and ecosystem agreements creates a demanding and unpredictable environment for cities to navigate. Cities are under high pressure to cluster and build avenue for new economic models, embrace green and circular economy concepts, and adapt to changing geopolitical scenarios as state aim to remain at the forefront of the digitization and data economy. At the same time, local authorities are expected to preserve and improve their residents' well-being and digital capabilities while effectively using ICTs, upgrade their technical infrastructure to deliver greater citizen-centric SC services.

Needless-to-say, cities necessitate a holistic approach that integrates pressures from landscape changes, Ecosystem Agreements, and the Finland Digital Compass to properly manage these challenges and anticipate possibilities. SCDT creation and deployment are critical in this setting because they provide a strong tool for optimising city infrastructure, boosting services, and promoting public engagement.

A forward-looking policy design that considers socio-technical perspectives of technological breakthroughs, societal well-being, system actors' communication, economic sustainability, and environmental awareness is required. Cities are expected rigorously develop and execute SCDTs that are tailored to their specific needs, utilise ecosystem agreements obligations, and actively contribute to the national (Finland's Digital Compass) and local desired future visions, simultaneously. IPRM offer cities to stay ahead of the transformative race to become more competitive, resilient, smarter, and innovative in the face of fast changing landscape dynamics and global challenges.

3 Research Method and Analysis

This study is qualitative exploratory futures research. It examined the study objectives holistically, taking into consideration the multiple aspect of SCDT. To answer,

> **RQ1:** "What kind of future-oriented innovation policies are needed for the future of Finnish smart city digital twins by 2035?

The thesis focused on developing an innovation policy roadmap via IPRM approach to address the complexity of socio-technical system transformations within Finnish cities. The objective was to analyse current SCDT understandings among related stakeholders and explore future-oriented innovation policies that can facilitate the systemic socio-technical transformation of Finnish SCDTs by 2035.

Literature findings revealed that to achieve the research aim, it was required scrutinizing the systems-thinking on cities as socio-technical systems, and SCDTs as cyber-physical complex systems of cities' socio-technical systems. So, the purpose of this qualitative future research revolved around comprehending the phenomenon's retrospective transformation, and current mainstream issues, conceptual and epistemological aspects. Hence, current issues concerning the future of SCDTs should be explained so that they are consistent with the interpretation, while it was vital that the study's methodology is compatible with the issues in literature and conceptual foundations.

The resources provided in the literature review served as the foundation blocks for the research process. For example, the Technology Roadmap subset of the IPRM comprises the virtual layer SCDTs and capabilities, and the digital layer includes the six SC dimensions proposed from the literature. There were two key reasons why the literature review ought to be broad and comprehensive but separate. First, to give solid and reliable guidance to those who are interested in the conceptual underpinnings of the prospective SCDT developments and recognising its cyber-physical systems-thinking blocks. Second, the theoretical and conceptual frameworks in referenced literature was intended to provide a solid basis for strong scientific reasoning to the IRPM.

A reminder, even if we cannot predict the future of smart cities, we can and should present the alternative desired futures depending on the drivers pressuring city systems and anticipating trends might shape future cities (Dator, 2019). Hence, as futures researchers, we can present forward-looking policy designs in accordance with the preferred future visions. Based on the data obtained from the literature review, cities have undergone systemic changes throughout history depending on external factors and will continue to undergo systemic changes in the future. However, in today's world, where modern technological developments are difficult to catch up with and unexpected phenomena are observed more frequently, the integration of DTs into city-scale systems seems to bring many opportunities but some vital challenges along with.

In addition to the conceptual and structural difficulties that already exist in the SC phenomenon, the DT, which harbours a much more complex system, makes this systemic complexity on cities even more complex. Therefore, literature review revealed the necessity of a holistic socio-technical approach based on systems-thinking, combining a shared vision considering cities' own needs and socio-technical system dynamics as well as inclusive technologic, innovation, strategic, and political conceptualizations and roadmapping approaches.

The idea of a SCDT systems-thinking could be approached from several perspectives. Collaborative perspectives such as Quadruple Helix (Hämäläinen, 2021;Raes et al., 2021) emphasises the involvement of organisations such as universities, R&D centres, and local authorities, businesses in the birth and dissemination of innovations. For example, that is one aspect of Finland Ecosystem Agreements. Another viewpoint emphasises the dynamic interactions between sociotechnical environments and niche-level developments (Geels, 2010; Geels & Schot, 2007). The practical research undertaken by the Demos Helsinki research team in Finland demonstrates that MLP is extremely successful in the development of smart cities (Neuvonen et al., 2015). At the level of scenario building (backcasting or forecasting) and execution, each of the layered scenarios offered by MLP based on its three primary levels provide a real instrument for future-oriented socio-technical shifts in policies to retrofitting future smart cities. While Fryszman et al. (2019) emphasize "smart mobility transition" on the socio-technical system of smart cities is a micro-scale system perspective, Geldenhuys et al. (2018, 1) state "Cities can be understood as complex socio-technical systems-of-systems and should be approached holistically due to their interdependence and interconnectedness,".

However, Boulanger, (2022) conducts wide-ranging study on "smart cities" and "roadmapping", and the study reveals that roadmapping culture mostly involves overlapping viewpoints on *technology roadmapping domain* such as blockchain, AI, ML, and IoT on the foundation of smart cities. Yet, Ahlqvist et al. (2014) remind that despite systemic decline, limited opportunities, and increasing competitive pressures, roadmapping plays a beneficial function as a policy instrument for regions or industrial sectors to build a strategy for renewal and transition.

Foresight is the backbone of causal linkages among those perspectives. Futures research emphasises the importance of foresight in leveraging information about how organisations scan their environment for change, detecting pressuring signals and design numerous alternative futures actions rather than forecasting (Heger & Rohrbeck, 2012; Rohrbeck & Bade, 2012; Rohrbeck & Gemünden, 2011). Furthermore, foresight in futures research investigates the creation of desirable visions and the integration of system components into a unified organisational response system (Højland & Rohrbeck, 2018; Rohrbeck et al., 2015; Rohrbeck & Gemünden, 2011; Schwarz et al., 2020). This holistic strategic foresight perspective helps organisations to adapt and respond to dynamic and unpredictable landscape changes strategically as well as enables “smart communication” within system to increase the policy-making bandwidth (Da Costa et al., 2008, 16). According to Ahlqvist et al. (2012, 179), foresight develops “new social structures” and links that aid in the movement of comprehension throughout the system and thus, various system features, such as actor assemblages, enabling technologies, temporal scope, and geographical scales (local, regional, national), must be addressed when designing successful policies in the system transformations. Thus, IPRM puts critical components of these causal conceptual building blocks on a solid foundation with systemicity, foresight and forward-looking policy design, and has features that are appropriate to the nature of this research (Ahlqvist et al., 2012, 179–180).

The IPRM method is the result of various project initiatives completed at Finland's VTT Technical Research Centre on different cases such as Nordic ICT Foresight and ICT for Environmental Sustainability (Ahlqvist et al., 2007; Ahola et al., 2010). Since then, its development is still ongoing and recently IPRM nurtured new frameworks called “Mission-oriented Innovation Policy Roadmapping” for use case for Sustainable Development Goals and Ahlqvist et al. (2012) is cited in this work (Miedzinski et al., 2019).

Yet, this research is first of its kind in both ways by utilizing IPRM on systemic transitions of SCDT phenomenon and providing alternative valuable perspective for the research gap on forward-looking policy design for future Finnish cities context.

Given that, in the following section, IPRM is introduced and explained why it provides a robust understanding for the Finnish SCDT vision. Then, based on the IPRM reference guide (Ahlqvist et al., 2012), the five phases of the IPRM are proceeded step by step. Based on the primary and secondary data source findings, the final "Innovation Policy Roadmap: Future of Finnish Smart City Digital Twins - Vision 2035" and its main blocks are explained.

3.1 Data Collection: Innovation Policy Roadmapping

IPRM is an integrative method that incorporates the two roadmapping cultures: technology and strategy, with a focus on the systemic dimensions of socio-technical transitions (Ahlqvist et al., 2012, 180). We can see the roadmapping cultures in hundreds of different forms, depending on the desired purpose or vision in the discipline in which it is applied (Kostoff & Schaller, 2001; Phaal et al., 2004; Phaal & Muller, 2009; Schallmo et al., 2017; Teece et al., 1997; Weber et al., 2009). From the work “Roadmapping Bibliography” by Robert Phaal (2015), who has made a name for himself in this field, it can be understood that the culture of roadmapping is very rich, and conceptually and empirically has found its place in more than 700 unique scientific documents, from sustainability to technological innovations, from business modelling to space technology product roadmapping.

In the context of IPRM, technology roadmapping acts as a normative tool for identifying relevant technologies and aligning them with product plans and actionable processes for product development. This strategy focuses on rigorous management practises for innovative product creations. Strategy roadmapping, on the other hand, adopts a dynamic and iterative method to visualising an organization's long-term goal and short- to medium-term strategies for achieving that vision. Roadmaps are viewed as visual tales that depict essential avenues for future advancements. In that sense, IPRM offers a complete study of technical improvements, policy designs and strategy practises, and landscape trends by merging these two roadmapping cultures. It encourages a more holistic socio-technical perspective and future-oriented approach. That, the findings of literature review revealed what future of Finnish SCDTs might need.

In the context of DT applications in Finnish smart cities, IPRM provides several policy rationales for forward-thinking policy designs. To begin, by creating a shared vision across stakeholders, a collaborative approach may be developed, encouraging commitment and alignment towards long-term goals. This unified vision can serve as a guiding beacon for SCDT development in the future. Second, IPRM may support systemic change by identifying systemic transformation requirements in Finnish cities that generate demand for DT solutions, addressing global concerns and their intersection at the local and national levels.

IPRM's Policy Rationales in the Context of SCDT

IPRM offers five core policy rationales for forward-looking policy design (Ahlqvist et al. 2012, 181). In the context of DT applications in Finnish smart cities, firstly, by building a common vision among stakeholders, a collaborative approach can be fostered, stimulating commitment and alignment towards long-term goals. This unified vision can serve as a compass for guiding the future of SCDT development. Secondly, IPRM may support systemic change by recognising the demands for systemic change in cities that generate requests for DT solutions, addressing global concerns and their intersection at the local and national levels, and addressing global difficulties at the global level. A simple example is that climate change as a global challenge is found in almost all Finnish policy papers, with the vision of a "green transition" aimed at systemic change. The disparity is based on a perspective that it is far from a holistic vision approach. With the idea of digitalization and data economy on green energy for mobility, traffic congestion, and increasing energy needs predominating in southern Finnish cities such as Helsinki, Turku, and Espoo, where population density is relatively high. Because the towns of northern Finland, which have damp and humid natural structures, are experiencing floods and emerging fly viruses to which Finland is not familiar because of climate change.

Third, by anticipating tensions in socio-technical city systems, when and how demand for DT enabling technologies may develop, new windows of opportunity for businesses and start-up ecosystems may be presented. As a result, it can help overcome hurdles such as vendor lock-ins, scalability of SCDT applications and high switching costs, as well as the lack of appropriate high-level interoperability mechanisms. Fourth, via cross-over understanding, especially among system regime players, visionary strategizing can improve comprehension of how complicated smart city digital twin cyber-physical systems are. It also aids in identifying drivers, regulations, and enabling technologies and possible policy solutions that can align and affect one another. Finally, IPRM can be used within the SC roadmap structure to identify specific innovation targets, such as key DT technologies for the local context or logical temporal sequences, while acknowledging the interconnected elements and linkages within the complex systems.

3.1.1 Depiction of IPRM

IPRM incorporates two levels of assessment the **Systemic Transformation Roadmap** and the **Technology Roadmap** as transformation enablers. As seen in **Figure 7**, the systemic transformation roadmap incorporates with four levels. First level is drivers. They are the great challenges in landscape level which put pressures on socio-technical systems and might trigger niche novelties to break the mainstream and align within it. Other levels are policy practises, and sectoral developments. It provides a comprehensive picture of holistic perspective. Policies level evaluates policy instruments and regulatory changes in the context of a dynamic socio-technical environment, considering socio-technical regime relations to conditioning variables and visualising the logic of policy choices. The sectoral development level focuses on emerging solutions as well as anticipated convergence and disruptions, establishing the environment for future-oriented market policies. The key enablers level is concerned with technologies and key enablers that facilitate sectoral development as well as socio-technical transition.

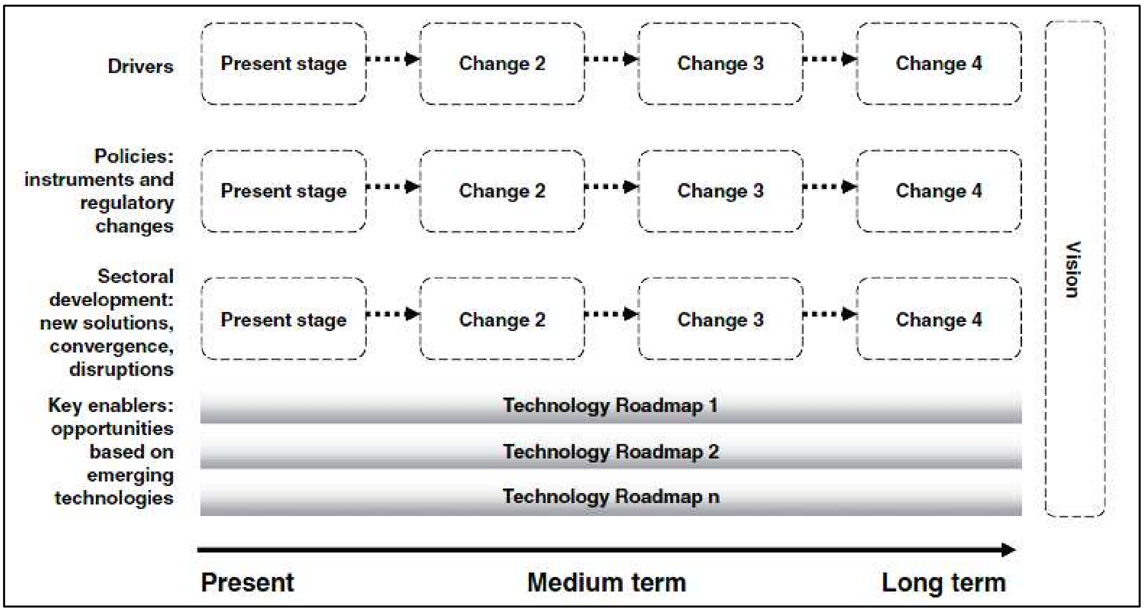

Figure 7. Generic structure of systemic transformation roadmap (Ahlqvist et al. 2012, 182)

Specific enabling technology roadmaps may or may not be necessary depending on the context since they can be successfully incorporated into the systemic transformation roadmap (Ahlqvist et al. 2012, 181). However, in the main context of the research, the technology roadmap was processed separately since SCDTs as cyber-physical system is necessitated to be examined in parts due to its complex system structure based on the findings of the literature.

Figure 8 portrays the technological roadmap, which is an integral part of the systemic transformation roadmap. It ideally does have four *potential* levels that are determined based on the research topic at hand. At the first level, technology-based solutions are shown, with an emphasis on specific technical breakthroughs deemed important. The second level depicts the enabling technologies and prospective technological convergence that helps in the implementation of these solutions. Rather than treating technologies as separate entities, this practise enables for a dynamic examination of changing structures. Also, *in certain cases*, in addition to second level enabling technologies, the technology roadmap may incorporate third level (market development) and the fourth level (involvement of players) (Ahlqvist et al. 2012, 182). However, in context of this research third and fourth levels were not utilized in **Figure 8**.

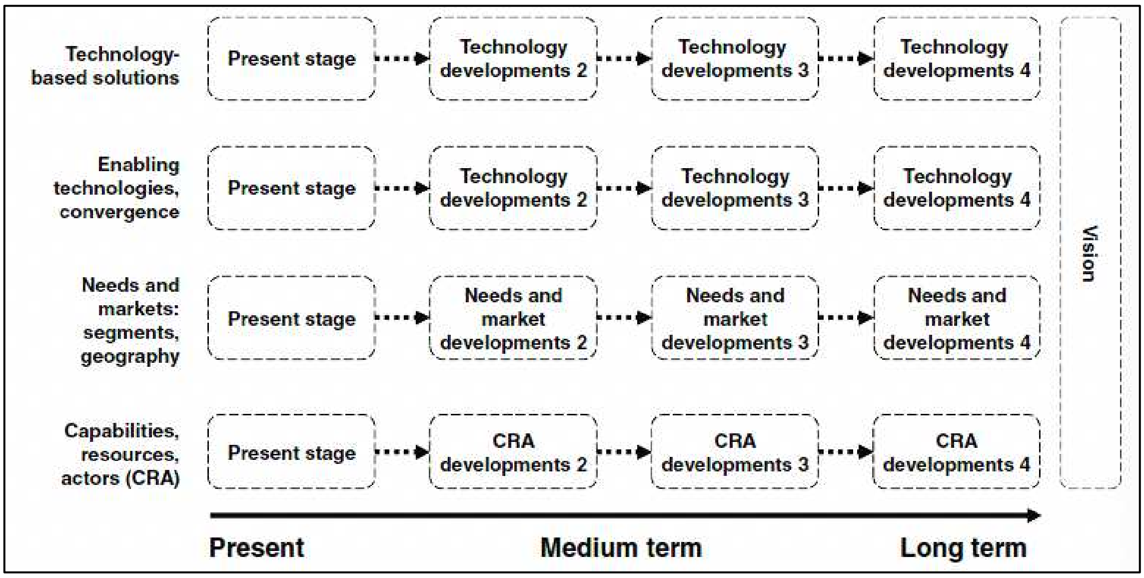

Figure 8. Generic structure of technology roadmap (Ahlqvist et al. 2012, 183).

The ideal aim by utilizing IPRM in the SCDT context were to integrate the state-of-the-art enabling ICTs and technology-based solutions in technology roadmap. The landscape drivers resulting pressures on Finnish cities' socio-technical systems to the extent of novelties, policy, and sectoral levels (– or socio-technical level) were analysed. By conducting interviews, this study evaluated multi-level real-life challenges and mismatches, and eventually provide feasible future-oriented policy-design perspectives in the context of systematic transitions for future Finnish SCDT within Vision 2035.

3.1.2 Roadmapping Process

The roadmapping processes based on the original guide reference arranged in 5-phases to the extent of the research's aim and objectives (See, **Figure 9**).

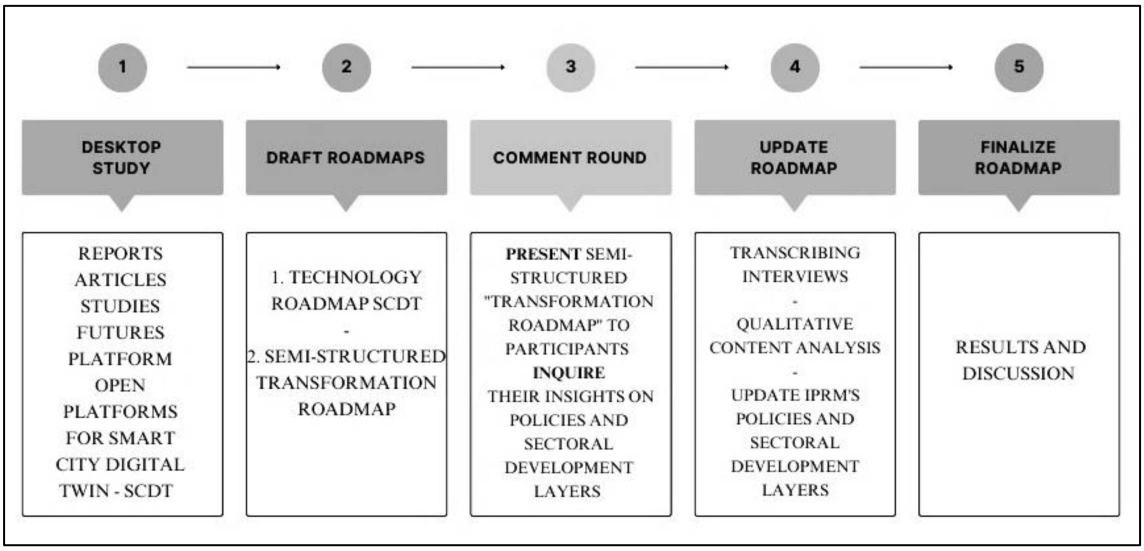

Figure 9. IPRM research phases

Phase 1 (Desktop Study): It starts with scanning the landscape. During this preliminary stage, knowledge is gathered through a systemic procedure that includes core literature scanning as provided in literature review section. Preliminary goal was to explore key conceptual approaches and comprehend the SCDT phenomenon in-dept as well as provide building blocks of IRPM for the roadmapping process. However, due to the reasons described in the research limitations, there were certain deviations from the original roadmapping process.

For example, in developing the IRPM's outline, the basic needs of diverse expert inclusion and iterative assessment and elaboration workshops were obviously not achieved. Nevertheless, significant efforts have been undertaken to alleviate any shortfall that may result from this. In addition to the materials in literature review, the desktop study including "Futures Platform Radar: Future Cities" (See, **Appendix 2** Futures

Platform Radar "Future Cities: 2035) and trend analysis from Futures Platform's foresight radars, which were accessed with special authorization for this research since it is not an open-source platform. Hence, the Futures Platform has over 1500 trend, phenomenon, and scenario analyses, as well as over one million current signals and hundreds of worldwide futurists who are specialists in their disciplines (About Futures Platform). Futures Platform serves numerous agencies and organisations, including the European Commission, on future research. Furthermore, papers, reports and research articles including trends, weak signals, and wild cards on SCDT were scanned using the Futures Platform's Horizon Scanning guide (Futures Platform Horizon Scanning). Notably, Finnish research organisations such as VTT, Sitra, and Demos Helsinki as well as International organizations such as Gartner, PWC and Deloitte; and Corporations such as IBM, Microsoft, Nokia and Siemens were considered with inclusion criterion of "Smart City" and "Digital Twin" and/or "Smart City Digital Twin" working groups, solution technologies or services and research domains as a must for considering supplementary materials to fill the gap.

In accordance with the case studies that paved the way for the development of IRPM, the sources used in the desktop study were kept different from the collective bibliography for both roadmaps and were added separately to the appendices to avoid complexity. To facilitate detailed examination, if desired, IPRM Desktop Study Info Pack excel file can be obtained via shared link in the appendixes.

See, **Appendix 3 Transformation roadmap desktop study results**.

See, **Appendix 4 Technology roadmap desktop study results.**

Phase 2 (Drafting Roadmaps): As a result of meticulous work in this step, IPRM's two main components, "Transformation Roadmap" and its subset "Technology Roadmap", were drafted to look deeper into the highlighted themes.

The drafts were presented in the "comment round" referred to by the original guide (Ahlqvist et al. 2012, 183 & 186). To get solid insights at **Phase 3,** a single excel file with draft roadmaps and glossary was sent to the experts before the interviews. Hence, during six consecutive interviews, both drafted roadmaps were also presented during actual interviews to obtain informants' insights.

Phase 3 (Commenting Round): This stage aims to ensure that varied insights are considered to update and finalize the IPRM. At this phase, the research was further enriched with expert insights as primary data to update IPRM. The primary objective was to obtain demand-side various insights on national policy visions (i.e., Digital Compass and Ecosystem Agreement) and current local policy strategy disputes and challenges from nation-level (ministerial) and local-level city experts conducting projects on smart cities and DTs.

In accordance with the scope and purpose of the research; to collect supply-side policy insights, industrial multinational and local companies providing services for various SCDT applications in Finland were invited. However, although various attempts were made to them participate in this research, there was not any positive response. It seems that the biggest factor in their rejections were company policies and Non-Disclosure Agreements. In short, as it revealed in the literature findings, the idea of a closed system prevails in the SC and DT sector. Thus, except the participant from FFRC, interviews insights are limited by only public authorities' demand-side policy insights interested in future-oriented cooperation on improving joint efforts on SCDT developments in Finland.

Semi-structured online interviews (See, **Table 11**) were conducted and recorded via Zoom application for comment round on draft IPRM. The comment round was completed through joint and single online interviews with total seven questions (Available in **Appendix 5 Interview questions and interview guide**). Joint interview participants from the city of Turku, including P1, a senior specialist with almost 20 years of experience in City Information Modelling - CIM, and P2, who has been engaged in SC management for five years. From the city of Tampere, insights were gathered from P5, who has a background in automation technology, involved in Finland's national artificial intelligence programme named "AuroraAI" and has been working on citizen DTs; P6, with a strong academic background and expertise in smart cities, safety, security, and resilience projects; and P7, a development manager involved in SC development. Additionally, single interviews were conducted with P3 from the city of Vantaa, who is a project manager involved in the Finland Ecosystem Agreements projects; P4, from the city of Helsinki - Forum Virium, serving as the product owner for the city DT; P8, from the Finnish Ministry of Transportation and Communications, with extensive experience in various fields related to digitalization; and finally, P9 from the Finland Futures

Research Centre, who has worked with energy and climate and has experience in SC and researches in DTs.

Table 11. Primary and secondary data sources.

Primary Data: Interviews			
	Organization	**Role**	**Experience in SC and DT**
P1	City of Turku	Senior Adviser of City Information Model	~20 years in GIS Coordinator, 10 years Smart City and DTs
P2	City of Turku	Strategy and Development Director	+20 years
P3	City of Vantaa	Project Manager Ecosystem Agreement	2 Years Ministry, + 2 Years Finland Ecosystem Agreement Programme
P4	Forum Virium - City of Helsinki	Technical Specialist	~10 years - 3D City Modelling - GIS - AR"
P5	City of Tampere	Director of Digital Transformation	~8 years
P6	City of Tampere	Head of Project	~20 years
P7	City of Tampere	Development Manager	~6 years
P8	Finnish Ministry of Transport and Communication	Senior Adviser	~7 years
P9	Finland Futures Research Centre – FFRC	Futures Researcher, Project Manager	~12 years
Secondary Data: Materials			
	Transformation Roadmap Desktop Study Results		
	Technology Roadmap Desktop Study Results		
	Materials referenced in literature review and research		

Online interviews were managed via Zoom with personal links and passwords. More than 8 hours recordings were transcribed into almost 45.000 words. In this process, no automated AI-powered online applications that promise up to 90% accuracy or any tools that allow the audio file to be uploaded and transcribed automatically were used. On the contrary, in this process, a controlled transcribing approach was followed due to the ethical values pursued for the protection of the data. Recordings were opened in a separate window and simultaneously transcribed with 100% accuracy in a controlled manner with the dictation feature of the Microsoft Office Word. Recordings and transcripts were kept in two different flash drives not in internet clouds.

3.1.3 Multi-level Analysis of Expert Insights on IPRM

For qualitative data analysis, iterative examination in Nvivo12 was conducted with MLP's multi-level analytical approach-based coding. Coding includes assessing the informant insights at three distinct levels: landscape (MACRO), socio-technical systems (MESO), and niche (MICRO). The focus at the landscape level is to comprehend the larger context and impact of changes in drivel level in Transformation Roadmap of IPRM and pressures on the Finnish cities in the context of SCDTs within socio-technical landscape. Global trends and its correlation to high-level policy frameworks such as Finland's Digital Compass, recent Finnish Innovation Policies 3.0, Ecosystem Agreements, and the role of Finnish cities within this complex environment were all considered to explore current causes of regime selection pressures (Smith et al. 2005, 1496), and characteristics of contemporary Finnish transformation pathways (Geels 2011, 32; 2019, 194; Geels & Schot, 2007, 406–413; Smith et al. 2005, 1499–1502).

Moving up to the socio-technical system (Meso) level, the research aimed to uncover the possible systemic shifts that recurrent mismatches and windows of opportunities may cause in Finnish cities while focusing on two Policies and Sectoral Development levels of Transformation Roadmap. This entailed investigating the interactions between national visions and its pressures on local socio-technical regimes; technology, governance, industrial, society, users, and urban infrastructure, as well as investigating how the actor-oriented policy integrations and use of feasible ICTs on DT solutions may result in significant future changes in future-oriented urban design, citizen-centric service delivery, regime collaboration and involvement for resilient future Finnish smart cities.

At the Niche (Micro) level analysis focuses on experts' distinctive local experiences, start-up ecosystems, ideas, and innovation issues. Especially Technology Roadmap in Key Enablers level of IPRM and Meso levels considered for this analysis. Their expertise in a variety of fields, including city information modelling, SC dimensions, safety and security management, and citizen DTs, gave essential views for comprehending the complex nature of SCDT applications as well as it can shed light for new novelties which can eventually align to the SC socio-technical mainstream.

The primary goal of multi-level analysis was to investigate participants' opinions and perceptions regarding existing studies in literature and the levels of IPRM constructed with desktop study results. The research directed to get an in-depth explorative understanding of the possible forward-looking actor oriented and systemic policy adoptions required for the effective integration of ICTs and utilisation of SCDTs in the Finnish environment by 2035 considering **Macro, Meso, and Micro-level** analysis. The objective of the MLP analysis process was to bridge the gap between theoretical concepts in literature and real-world expert perceptions, giving significant feedback for refining and modifying the IPRM to address the complexities of socio-technical system transitions for future smart cities in Finland. The first six interview questions are dedicated to achieving this goal.

Phase 4 – 5 (Update Roadmaps and Finalize): The roadmap is updated after incorporating expert feedbacks and insights and finalised by making required revisions. The complete IPRM aids foresight in the direction of forward-looking policy design construction and holistic strategic transformation activities, and offer a clear path forward the Future of Finnish SCDT developments.

3.2 Data Analysis and Findings: Innovation Policy Roadmap on the Future of Finnish SCDT Vision 2035

IPRM is an integrative method that incorporates the two roadmapping cultures: technology and strategy, with a focus on the systemic dimensions of socio-technical transitions (Ahlqvist et al. 2012, 180). In this section literature findings and multi-level analysis of informant's insights were fused to provide a clear depiction and keep integrity of research. For example, after providing drivel level findings macro level analysis was also presented. Likewise, since policies and sectoral developments plays a vital role in city's socio-technical systems-thinking, right after findings in these two levels of IPRM, Meso level informant insight analyses were provided with policy suggestions.

Outline of Transformation Roadmap

In line with the scope and RQ1 objectives of the research, the aggregate foresight insights from primary and secondary data sources were crystallized in **Figure 10**. The baseline of the roadmap for the Finnish SCDTs, visioned with the goal of 2035, is following:

> Finland and Finnish Cities aspire to be a digitally competent, carbon-neutral, welfare state by 2035, with trustworthy and secure digitalization that fosters digital competence and data-driven ecosystem through cutting-edge technology. Finland

focuses on environmentally friendly, human-centric, and sustainable data economy solutions, creating an inclusive society through extensive digital education. Finland desires to attract skilled foreign IT professionals and enterprises by providing a competitive environment, promoting healthy growth, internationalisation, and societal well-being. With the aim of achieving this vision against external factors, the current innovation perspectives include a collaborative distribution of tasks to Finnish cities. In parallel, with those objectives might also pave the way prospective *Finland National Digital Twin Programme* foundations while achieving SCDTs, substantially. 2028 is the mid-term based on the Finnish Ecosystem Agreements, and 2035 is inspired by both the Finland Digital Compass (2030) and the strategic goals of common Finnish cities (2035).

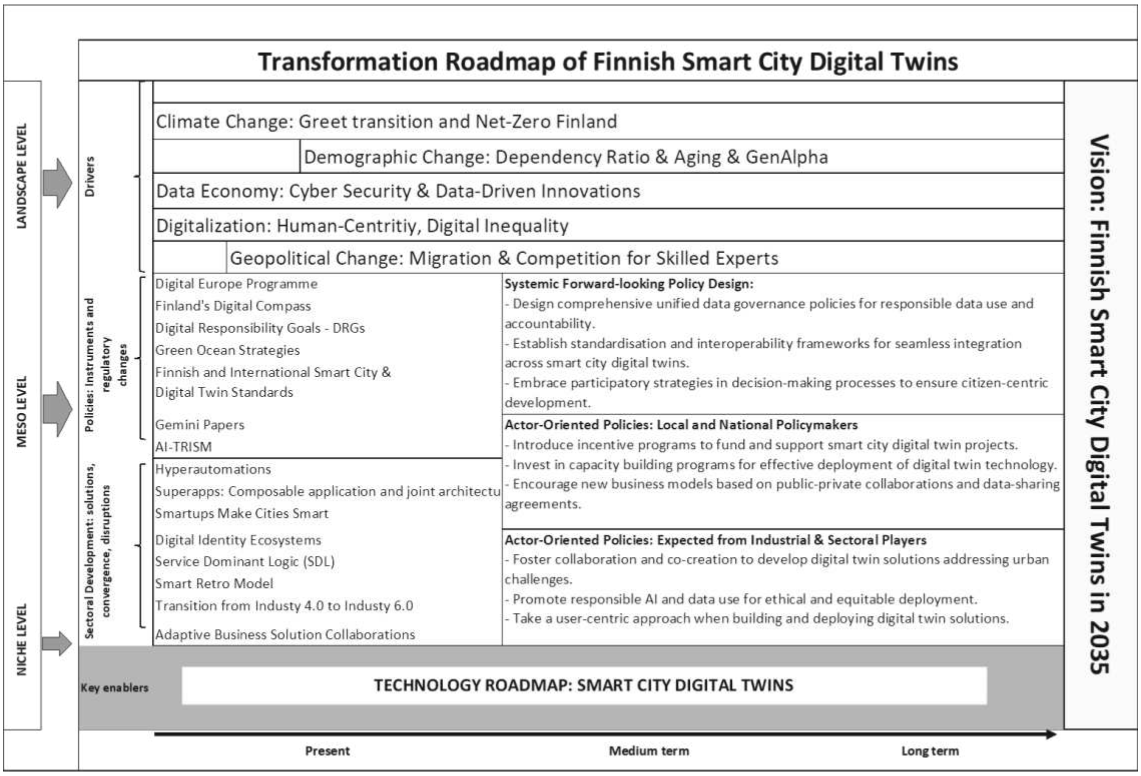

Figure 10. Transformation roadmap of smart city digital twin, Finland.

3.2.1 Drivers

Climate change, demographic change, data economy and digitalization, geopolitical change, and global migration are all key drivers of SC development in Finland. In response to climate change, smart cities are adopting ICTs for sustainable green transitions and circular economy ideas to adopt and lead the Net Zero World Concept, which focuses on lowering carbon emissions and boosting environmental sustainability. Smart mobility and smart energy projects are being developed in the digital layer to optimise transport and energy consumption for increased efficiency.

Demographic change is pushing the need for innovative solutions to address issues such as the dependency ratio and the ageing population in Finland. Efforts are also being made to combat digital inequality and exclusion, ensuring that technology improvements benefit all parts of the society. The shifting attitudes of Gen Alpha, the younger generation, have an impact on the design of SC solutions in the digital layer, which attempt to meet their future requirements and desires for a connected and digitally integrated urban environment.

While cities are becoming increasingly urbanised and data-driven, the data economy and digitalization are driving new company operating models. However, this transition raises worries about cyber security, which, if not managed effectively, might lead to a decline in trust in political decision-makers. Smart economy projects are being implemented in the digital layer to capitalise on the promise of data-driven innovations for economic development and efficiency.

Geopolitical change and global migration are having an influence on SC development by raising competition for skilled IT professionals and escalating race between nations. Cities are developing open data platforms while dealing with possible cyber threats and smart city attacks. Smart governance is critical in the digital layer for managing and navigating these geopolitical problems, guaranteeing safe and efficient data processing while encouraging openness and public involvement.

Overall, the drivers are interrelated and impact the many characteristics of Finland's smart cities' digital layer. To create resilient and inclusive SCDTs, policymakers and stakeholders need to work together to address these issues, supporting sustainable, equitable, and technologically advanced urban environments for the well-being of all Finnish inhabitants.

3.2.2 MACRO – Landscape Level Analysis and Findings

Several drivers were identified based on informant insights that are especially essential in the context of the SCDT socio-technical landscape level.

Despite various drivers play crucial roles in defining the socio-technical landscape in the Finnish SCDT development, climate change has emerged as a major driver, demanding Finnish cities and ministries thorough mitigation and adaptation efforts. Another major driver is the data economy. Cities struggle with data ownership, privacy, cyber-security, and the limitations of cross-sector collaboration while attempting to leverage the potential of data silos already exist in cities for new DT solutions. The continuous digital transformation process is visible, with cities leveraging technology to improve urban planning, citizen services, and data management. As cities recognise the importance of preserving their digital operational environments to retain trust and confidence, cybersecurity has emerged as a critical factor. Demographic trends, such as an ageing population, urbanisation, and dwindling faith in political decision-makers, all have an impact on the planning and execution of SCDT initiatives. Cities are being pushed to embrace smart solutions that adapt to the requirements of a dynamic world and national goals while maintaining their strategic local aims, diversity, sustainability, and citizen well-being in this ever-changing landscape.

Various pressures have been analysed from informants' insights in the quest of establishing SCDT projects, altering the socio-technical landscape. On the one hand, data utilisation, environmental concerns, innovation policy, and data-driven economic issues appear as significant forces driving SC advancement. The potential for data-driven solutions, climate change mitigation, citizen-centric innovations, and economic development renders stakeholders to make radical changes. However, these drivers face enormous challenges that must be properly handled.

3.2.3 Policies

The forward-looking policy design approach with the Finnish SCDT begins by considering the socio-technical systems of cities and the regime dynamics of this system by considering the reasons mentioned above. First, there is the innovation 3.0 shift starting from 2020s, Finland's Digital Compass, which takes its main lines from the Digital Europe Program, and the Ecosystem Agreements, which sets the criteria and objectives of systemic transformation within the framework of this national innovation for cities.

Compliance with big data and related data governance legislation poses complicated issues in enabling cross-sectoral data collaboration while protecting individual privacy. Furthermore, technological and infrastructure deficiencies, as well as local authorities' skill, time, and budget restrictions, impede the full potential of SC technological advancements and eventually feasibility of DTs in cyber space. Geopolitical and security considerations increase worries about the possible exploitation of Finnish individuals' data in cities' open data platforms, demanding strong cybersecurity measures to maintain system confidence. Legal and regulatory constraints impede local administrations' capacity to collect and use data efficiently.

Initial analysis revealed that, Finland Ecosystem Agreements (2021-2027) might serve as foundational grounds for developing Finland National Digital Twin Program by 2027. These agreements can foster cross-sectoral solutions to urban difficulties by bringing together the citizens as users, public sector as policy makers, commercial firms as industrial actors, research institutes as science and technology, and civil society for cultural meanings and discourse changings. Collaboration might result in the development of complete standardization for Finland's National Digital Twin Programme that leverage the upskilling and knowledge amendments of regime actors. The problem, however, is successfully coordinating and aligning the interests of many parties while also resolving diverse visions within the system. Building trust and attaining long-term goals will need open and transparent governing frameworks.

Based on the Desktop Results; Digital Responsibility Goals (DRGs), Nordic Smart City Roadmap, Green Ocean Strategies, Finnish and International Smart City & Digital Twin Standards, UK's National Digital Twin Programme Strategies: "Gemini Principles & Roadmap", EU's AI-TRISM, and Composable Policy Applications can be used as a guide in accordance with local needs and strategies of cities aligned with national visions embedded in Ecosystem Agreements and Digital Compass.

Findings revealed that those also might pave the way for a solid ground for National Digital Twin Programme by 2027 with the following policy design suggestions:

- Develop a national-level Digital Responsibility Framework that integrates the DRGs, guaranteeing that all enterprises participating in Finland's digital ecosystem adhere to responsible practises. The framework should prioritise current cybersecurity protections, privacy considerations during data collecting, data fairness even for non-personal data, data processing with trustworthiness aims, and clear communication of principles to stakeholders. Encourage businesses to embrace these goals willingly and consider giving incentives for compliance.

- Green Ocean Strategies for technical Advancement: Strengthen Finland's position as a worldwide technical leader by investing in R&D in critical sectors essentially in DT and digitalization, 5G/6G connectivity, AI, and autonomous systems. Encourage academic-industry collaboration to guarantee that knowledge and skill upgrade in DTs is strongly ingrained in Finnish industry. Create DT innovation centres and financing programmes to speed the development but not prioritize external funds as in Ecosystem Agreements and implement green technology for SCDT solutions that are sustainable.

- National Smart City and Digital Twin Standards: It is required to urge municipalities and businesses interested in SCDT initiatives to follow Finnish and international Smart City and Digital Twin Standards. Implement standards such as Finnish CWA 17381 for good practices in smart city solutions, ISO 37120:2018 Sustainable cities and communities — Indicators for city services and quality of life; ISO 37122:2019 for smart cities; ISO 37123:2019 for resilient cities and ISO 23247-1:2021 Automation systems and integration — Digital Twin Series. These standards might ensure interoperability, data consistency, and effective governance in Nation-wide scalable citizen-centric SCDT initiatives.

- Consider another national DT programme just as a model generation specific to the Finnish socio-technical ecosystem. For example, Gemini Principles of UK’s National Digital Twin Programme is result of joint effort with all system actors to govern high-level concepts which are based on purpose, trust, and function, on governing information management in the built environment and industrial activities. In that sense, Nordic Smart City Roadmap, "Moomin Valley: A New Narrative for Human-Centric Smart Cities” that define what Nordic smart cities look like by replacing technocratic models that seek to describe what a SC is. Concentrate on the characteristics of excellent governance of digital technology for municipal organisations and the qualities of cities outlined by employing ICTs the servant of people rather than the master. This narrative provides useful principles to encourage public-private partnership to sustain these ideals and produce creative solutions that are in line with the citizen-centric approaches in Digital Compass.

- To ensure feedback and develop open, data-driven, and trustworthy SCDT efforts, disseminate the essentials of Finland's present AuroraAI programme and MyData utilization for ethical AI deployment and national data governance with all stakeholders. Analysis has shown that while some cities consider MyData is prior options, some others plan to develop their own. That might hinder future unified data governance for connected National Digital Twin. Also, encouragement of composable policy applications may also help with agile governance, efficiently adjusting to changing demands while supporting local innovation. This multifaceted forward-looking policy approach will encourage responsible, sustainable, and technologically sophisticated DT initiatives throughout Finland, benefitting especially cities and inhabitants and contributing to Finland's global leadership in innovation.

3.2.4 Sectoral Developments

At present SC applications are revolutionising urban life in Finland in numerous ways. According to recent reports the Finnish SC Market is expected to show an annual growth rate of 11.84%, resulting in a market volume almost €1Bn and Finnish IoT Market with annual growth rate of 12.64%, resulting in a market volume of €9Bn by 2028 (Statista, 2022; 2023). In this regard, while Business Finland and Tekes take the lead in funding start-ups and vibrant Finnish Start-up Ecosystem enable SC applications in various dimensions, Nokia, Sitowise and other multinational corporations also play a significant role in the Finnish sectoral developments. The Mobility as a Service (MaaS) platforms, which integrates numerous transport alternatives into a single app with IoT sensors on public transit for real-time tracking, is a prominent example of a smart mobility efforts. A network of EV charging infrastructure built for smart mobility, with IoT sensors on charging stations for monitoring and smart grid integration for optimised charging. A smart waste management system uses IoT sensors to optimise waste collection routes and encourage recycling in the aim of a smart environment.

A health monitoring system using wearable gadgets and remote monitoring technologies improves the well-being of elderly individuals and energy-efficient smart houses with IoT devices for optimised energy usage and comfort enable assisting to thrive smart people within a smart environment. Finally, a citizen engagement platform encourages involvement in smart governance, with mobile applications and data analytics allowing input processing and transmission. These initiatives demonstrate how Finland is utilising cutting-edge technologies to build a connected and sustainable SC environment.

While those improvements taking place in Finnish SC sectoral developments, except specific development efforts such as in Tampere and Helsinki, SCDT applications still need a high-level concrete attention.

Future trends based on the literature and desktop study findings are as follows. For instance, Gartner predicts that 60% of government organisations would prioritise business process automation by 2026, up from 35% in 2022. Thus, Hyperautomation efforts help governments, cities, users, businesses, and ICT operators offer integrated and seamless citizen services. To drive digital transformation, governments and local authorities need to link automation programmes with existing goals while also optimising operating expenses. Also, Superapps seems to be considered as a collection of fundamental features and access to independently generated "Mini-apps" that allow for a consistent and personalised user experience within a single application nation-wide. Hence, emerging digital identity ecosystems offer a chance to implement the MyData concept on a national scale for Finnish SCDTs to improve citizen participation, trust, and security. Connected SCDTs can allow smooth and safe interactions within the SC ecosystems by providing high-assurance single digital identity solutions that are easily accessible and relevant to varied user groups and service providers.

Avant-garde sectoral policies are required for Finnish SCDTs to effectively utilise future trends. Government should focus on developing a high-level roadmap for integrating Hyperautomation technologies, foster collaborations for the development of Superapps, incentivize resource-efficient practises through grants and regulations, and establish robust data protection standards for digital identity ecosystems. Finnish local authorities and sectoral players can position its SCDTs as first and foremost open; and innovative, sustainable, and citizen-centric platforms by enacting these policies by 2027 and guaranteeing that they stay at the forefront of technology breakthroughs by 2035.

3.2.5 MESO – Systems Level Analysis and Findings

During meso-level analysis, priority was to identify whether the current challenge in literature has similarities in Finnish context and define correlating causes of the tension created by the pressures on the socio-technical systems of cities.

Informants' insights on efforts of SCDTs brings a variety of issues that need careful thought and collaboration. For example, the lack of a clear and broadly acknowledged definition of DTs for smart cities hinders progress since different stakeholders have varied viewpoints on their meaning, conceptual objectives, and opportunities. Funding restrictions and a shortage of skilled professionals are important impediments to the implementation and scalability of DT applications in cities. Integrating data from multiple sources and maintaining accurate data governance and privacy have become challenging obstacles, necessitating the use of a unified data infrastructure to enable seamless data exchange while respecting the privacy and data ownership of inhabitants.

Because of the technological complexity of DT systems, cutting-edge knowledge is required, which may not always be easily available in the public sector. As data-driven decision-making must balance advantages with citizen privacy, ethical and privacy considerations arise. It seems that it is vital for success to achieve a balance between short-term technical developments and long-term urban planning and policy-making. Collaboration across government departments and organisations is critical, as a lack of collaboration can result in duplication efforts other cities and wasteful resource and budget utilisation. A human-cantered approach is required to integrate technical breakthroughs with the needs of citizens.

It is critical for good communication and future-oriented collaboration between IT specialists, politicians, and urban planners to overcome cultural and organisational hurdles. Finally, tackling the complexity of SC systems with different stakeholders and purposes necessitates a comprehensive and coordinated strategy to build meaningful and sustainable SCDTs that improve urban living for all people.

3.2.6 MESO – Level Thematic Analysis and Findings

The thematic analysis of informant responses contributes useful information about the desirability, feasibility, and scalability of SCDTs in Finland. The responses revealed several themes. One recurring subject was the potential for DTs to transform urban planning and construction. The notion of employing DTs to plan and visualise existing and future city settings is considered as a significant tool for decision-making and citizen participation. Another recurring theme was the role of data and AI in driving DT success. Cities may construct predictive models and simulations using real-time, dynamic data from diverse sources, allowing for better planning, optimised operations, and enhanced service delivery. According to overall perceptions, smart mobility has the highest potential for this since analysis revealed that it has more matured in Finland than other five-SC dimension by considering externalities and interdependencies among them (people, citizens, governance, economy, and environment).

However, concerns have been raised vis-à-vis data governance, interoperability, and the need for scalable solutions. The informant responses emphasise the need of using a human-cantered approach, emphasising that the ultimate purpose of DTs should be to improve people' lives and well-being. Participatory approaches that engage inhabitants in the planning process are viewed as critical for effective implementation in this environment. The analysis also illustrates the difficulties in developing a shared vision for SCDTs. To attract public support and involvement, clear and compelling communication about the benefits and incentives for adopting SCDT applications is required. Furthermore, there is a desire for collaboration and coordination across cities and regions to minimise duplication of efforts and to develop scalable solutions that can be used in a variety of instances. The importance of learning, information exchange, and the formation of learning teams is emphasised as critical for effective DT adoption.

Overall, the analysis shows that, while the promise of SCDTs is thrilling there are complexity and obstacles that must be handled. Data governance, interoperability, public participation, scalability, and the formation of a holistic shared vision for SCDT development are all elements that policymakers and stakeholders should address in Finland.

3.2.7 MESO – Socio-technical System Level Pressure Analysis and Findings

Informants offer insight on the many pressures and issues that socio-technical systems encounter in the context of SCDTs. These problems cover a wide range of issues that are crucial to the effective and ethical application of such technologies included in the technology roadmap. First and foremost, data governance and privacy emerge as critical problems. The huge volume of data already created and will be processed by DTs needs sophisticated frameworks that protect data privacy while also assuring its security and ethical use. Second, interoperability is a considerable hurdle. Integrating various DT systems and datasets from various sources necessitates the use of a common platform or standard for data sharing, allowing for easy cooperation and integration. Third, citizen participation emerges as a critical component. Citizens must be involved in the development and execution of DTs to satisfy social demands and prevent top-down decision-making, generating a feeling of desired future ownership and planning inclusion. Fourth, the viability and scalability of DT technologies are being investigated. While the potential is enormous, establishing cost-effective and scalable solutions that can be implemented across several cities and regions remains an urgent problem.

Fifth, having a clear vision and communicating effectively are critical to gaining support and ensuring successful execution. Developing a high-level vision and integrated strategy for SCDTs and communicating their advantages to a wide range of stakeholders, including the public, legislators, and industry actors, is critical to achieving good change. Finally, the rapid pace of technological progress creates both possibilities and difficulties. Policymakers and stakeholders should keep up with technological advances such as AI, IoT, ML and XR, while also ensuring that DTs are adaptive and future-proof. To navigate these problems, first and foremost, Smartup initiatives (Start-ups that provide innovative ideas for SC applications against city's problems) within vibrant Finnish Start-up Ecosystem should be initiated. Also, national politicians, local and multinational companies, and communities need to collaborate to develop comprehensive SCDT solutions. The importance of data ethics, citizen-centricity, and open communication will be critical in realising the full potential of SCDTs while guaranteeing a sustainable and inclusive urban future.

3.2.8 Forward-looking Policy Design Suggestions for Future SCDT

3.2.8.1 Systemic Policies

- **Design Comprehensive Unified Data Governance Policies in Cities:** Policymakers in Finland ought to formulate comprehensive data governance policies for local authorities and SCDT suppliers that cover data management, privacy, security, ownership, and sharing. These frameworks should encourage openness and accountability while assuring appropriate and ethical data use.
- **Standardisation and interoperability:** Common standards for data interchange and interoperability are required to enable smooth integration of local SCDTs to Nation-wide connected DT ecosystem. Policymakers should support the creation and implementation of such standards to promote collaboration and synthetic data generation and sharing across various systems and third parties (businesses)

- **Participatory Strategies:** In city planning and development, policymakers should use participatory approaches. By including inhabitants and important stakeholders in decision-making processes, SCDT projects may become more inclusive and citizen-centric within feedback-loop of impact assessment and user expectations.
- **Innovation Hubs and Learning Networks:** National and local authorities should establish SCDT innovation hubs and learning networks to enable collaboration across cities, universities, and businesses. These platforms may be used to exchange SCDT information, best practices, and experiences, enabling continuous learning and growth. "The European Network of Living Labs – EnoLL" stands out as one of the rare hub formations that can meet this need. It is an independent, non-profit organisation that represents the European Network of Living Labs. Living Labs are real-world test and innovation settings using Quadruple Helix to encourage citizen collaboration and open innovation among people, government, businesses, and academia. Interestingly, while EnoLL was founded in November 2006 under the Finnish Presidency of the Council of The European Union (EU), only five Finnish organizations are among +480 European and international members namely, Lut University (Lappeeranta), Tampere University of Applied Sciences (Tampere), Lahti Living Lab (Lahti), Laurea University of Applied Sciences (Vantaa) and Forum Virium Helsinki (Helsinki). It seems that this needs to be spilled over among all Finnish cities or by clustering couple of small cities for a specific centre-hub.

3.2.8.2 Actor-oriented Policies: Local and National Policymakers

- **Incentive Programs:** Policymakers should guarantee to fund the SCDT projects not just providing venture fund and urge project stakeholders to find external funds. They need to establish incentive programmes to encourage cities and regions to invest in and use DTs in smart cities. New programmes can provide trust in the perception on the integrity of SCDT development by national financing, technical assistance, and recognition for successful efforts, encouraging cities to adopt cutting-edge technologies.
- **Capacity Building:** Policymakers should invest in programmes that provide training and capacity-building for local officials, policymakers, and technologists. Improving their awareness and abilities in efficiently deploying DTs would result in improved use of these technologies for urban development.

- **New Public Procurement Models:** Encourage new Business Models on Public-Private Collaborations based on non-patented solutions and data-sharing agreements. No – secrets – No – Vendor – lock – ins with new business models. This should be encouraged by policymakers. Data from diverse sources, including private firms, may be used to improve SC planning and services, resulting in more efficient and data-driven decision-making.

3.2.8.3 Actor-oriented Policies: Expectations from Industrial & Sectoral Players

Within the scope of the research, the insights from the informants as a demand-side, which are the beneficiary of the possible SCDT services provided, were synthesized with the information contained in the literature. These are only desired expectations based on informant's insights rather than a definitive policy suggestion.

- **Collaboration and Co-Creation:** To co-create and deploy DT solutions, industrial sector actors are expected actively work with academics, government agencies, and other stakeholders. They can recognise urban concerns and develop new solutions that satisfy demands while improving the whole ecosystem of cities by working together. By doing that they should consider new revenue streaming by business model innovations that are not dominantly based on competitive-advantage, secret "thing" or vendor lock-in strategies.
- **Adoption of Common Data Standards:** Players in the industrial sector are expected to accept and adhere to common data standards and interoperability criteria. This will allow their solutions to interface easily with city-wide DTs and other SC infrastructure, resulting in better efficiency and effectiveness in data interchange and utilisation nationwide.
- **Responsible AI and Data Use:** Sectoral actors are expected to adopt and promote ethical rules for the public good use of AI and data in DTs on a proactive basis. They can build trust with citizens and guarantee that technology is used for the broader societal good by prioritising ethical and equitable deployment.
- **Innovation and Research:** Industrial players are expected to join in open R&D&I to constantly enhance and reinvent their DT solutions. This will not only increase their competitiveness but will also help to improve SCDT applications in general.
- **Easy to manage Digital Twin Alignment with City Needs and Goals:** Sectoral actors are expected to link their DT offers with the urban environment's larger aims

and ambitions. They may become valuable participants in the SC ecosystem by tackling urban concerns and contributing to the city's improvement.

- **User-Centric Approach – Costumer or Consumer?** When building and deploying DT solutions, industrial players are expected to take a user-centric approach. Understanding and addressing people' and other stakeholders' desires and preferences will result in more effective and universally accepted solutions.
- **Scalability:** Sectoral actors should prioritise the development of scalable and reproducible DT solutions. This would enable their innovations to be implemented across several cities and regions easily, therefore contributing to the growth and extension of SC efforts and eventually connected SCDT in Finland.
- **Data Privacy and Security:** In their DT solutions, industrial players must prioritise data protection and security. Implementing strong data protection measures will increase citizen confidence and assure compliance with data legislation - a win-win, more data more service design for other city challenges.
- **Long-Term Commitment:** Sector stakeholders must show a long-term commitment to the SC ecosystem and DT efforts. Continuous participation and support can encourage long-term growth and have a beneficial influence on urban settings.

Industrial or SCDT business sector actors are likely to have a big role in creating the future of smart cities and DTs by achieving these expectations. Their cooperation, commitment to standards and ethical use of technology can assist to create more inclusive, efficient, and citizen-centred built urban environments.

3.2.9 Key Enablers: Technology Roadmap: Smart City Digital Twins

The final part of the IPRM involves the technology roadmap as a subset of the transformation roadmap. Reminding the perspective based on the SCDT cyber-physical systems-thinking in "**Figure 5. Smart City Digital Twins Cyber-Physical Systems Thinking** (Modified from; Lu et al., 2019; Mylonas et al., 2021; White et al., 2021).", this roadmap is based on the socio-technical systems of the cities represented in cyberspace. After a detailed review of literature and desktop study findings of technological roadmaps reveals a vital ensemble of enabling technologies, bringing the confluence of technology and urban dynamics to life (See, **Figure 11**). These enabling technologies layer act as delicate conduits, bidirectionally connecting the city systems in physical space with the vast options to the cyber space. This elusive interaction allows for an ensemble interchange of bidirectional data flow, encouraging not just SC solutions in six dimensions in digital layer but also their virtual representations in the form of digital models, digital shadows but desirably DT applications with various capabilities.

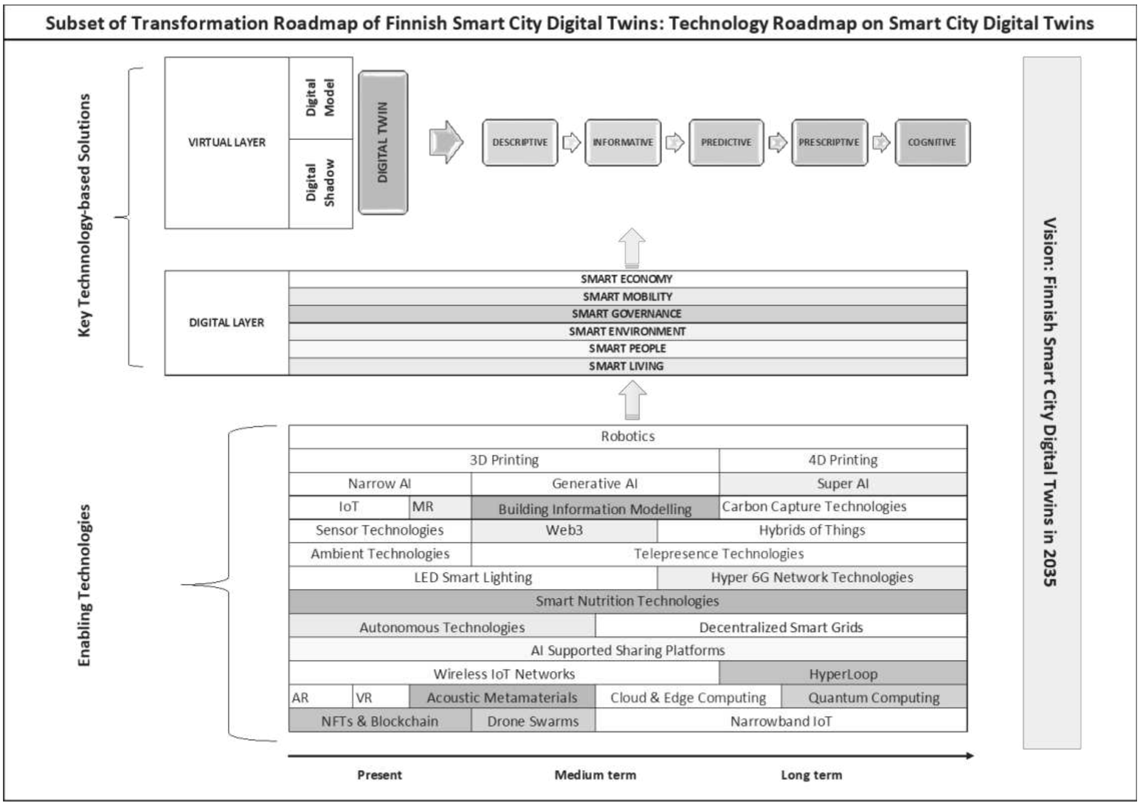

Figure 11. Technology roadmap as subset of the transformation roadmap of smart city digital twins, Finland

3.2.9.1 Enabling Technologies

Big data analytics, autonomous mobility, IoT, sensor technologies, and the progressive incorporation of AI and ML into current SC solutions are at the heart of the socio-technical shift of Finnish cities. Robotics and sophisticated printing techniques such as 3D and 4D are redefining the paradigms of building, nutrition (printed meals), health (manufactured organs), and automation. Narrow, Generative and Super AI boost intelligence by organising insights from enormous data silos created in city streams. The IoT breathes new life into urban infrastructure by connecting gadgets and providing real-time data for informed decision-making. These breakthroughs, coupled with Building Information Modelling (BIM) and Carbon Capture, constitute the foundation of a sustainable and efficient urban landscape development.

Meanwhile, Sensor and Ambient Technologies work together to produce a responsive digital layer that is seamlessly intertwined with the real city systems. This digital layer broadens its scope by utilising AR, VR Mixed-Reality, Cloud and Edge Computing, allowing for the integration of Web3, Hybrid of Things, and Telepresence Technologies. The symbiotic interdependence of these enabling technologies allows the formation of virtual presence of cities in which DTs of cities flourish. DTs with various capabilities are complex systems of system simulations that provide a virtual layer for testing new methods, anticipating urban dynamics, and improving decisions. As a result, physical and virtual layers coexist together, enhancing the present and creating the future of resilient human-centric cities.

3.2.9.2 Technology-based Solutions

According to a detailed analysis and an examination of emerging trends (See, **Appendix 4 Technology roadmap desktop study results**) the future of Finnish smart cities appears to be a dynamic combination of ICTs innovations and urban development via wide ICT integration. At present, in Finnish cities digital shadows and digital models are broadly utilized. Hence, AI, IoT, and Big Data Analysis are set to transform the socio-technical landscape in mid-term towards actual DTs by providing a seamless link between physical and cyber domains in longer period.

The Localization of Everything is one notable concept that promises to strengthen smart supply chain resilience. This localisation, enabled by technologies such as AR, VR, and 3D printing, provides a mixed reality in which the digital and physical space collide, encouraging a Hybridization of Society. Furthermore, the introduction of Hyper 6G Network Technologies and LED Lighting, together with Smart Nutrition technology advances, feeds the notion of Vertical Farming, converting urban spaces into centres of self-sustaining Agri-communities. The emergence of the 15-Minute City, a vision of efficient, self-sufficient urban life, is being projected by autonomous technologies and sharing economy services. This futuristic cityscape integrates Micro mobility and Noise-Blocking Technology, culminating in Noiseless Cities that prioritise the well-being of its citizens. The city's system is further knitted using wireless IoT networks, citizen DTs, creating the framework for an augmented Metaverse in which daily city services interact seamlessly with business, creativity, research, telepresence concept, academic and professional activities.

Transparent governance is aided by Non-Fungible Tokens - NFTs and Blockchain, while Autonomous & AI-Supported Drone Swarms alter urban air mobility. Airport Cities are evolving into multifunctional transit hubs that connect multiple means of transportation and services. Narrowband-IoT Technology ushers in self-optimizing municipal public service ecosystems, while Cloud and Edge Computing provide continuous connectivity. Telepresence Technology and Ambient IoT enable cities to be transformed into Ubiquitous Hubs that provide global expertise as well as local services. E-sports City Centres are cultivated by gaming technologies such as VR and AR, which develop a lively community of athletes and enthusiasts. Augmented Urban Reality provides a digital overlay to urban areas, increasing interactions and experiences.

Together with Floating Photovoltaic and Energy Grids, Sharing Economy Technologies produce All-Inclusive City Lifestyle Packages and sustainable energy solutions. Multifunctional Hybrid Buildings are enabled by Hyperloop and subsurface construction technologies, while Decentralised Smart Grids assure efficient energy distribution. Digitalization, IoT, and Cloud Computing solve Smart City Attack issues, boosting cybersecurity across several areas. Smart and Connected City Countryside extends urban advances to rural regions, promoting long-term development. Tactical Urbanism allows residents to shape their urban environment, whereas Forest Towns and Biophilic Smart City Designs encourage nature-inspired living.

Amid the unfolding variety of technical advancement and urban shifts occurring in Finnish smart cities, a novel trend signal is emerging that has the potential to transform the foundations of governance: the Machine-Assisted Mayor. This movement represents a paradigm shift in city management, integrating human inventiveness with artificial intelligence to drive efficiency and innovation. It is anchored on convergence of enabling technologies such as computing, AI, ML and IoT within virtual layer. The Machine-Assisted Mayor signal envisions a future in which AI-powered technologies collaborate with city authorities, providing real-time insights, alternative scenarios, and predictive data to help them make key informed decisions. These SCDTs can analyse enormous datasets obtained from Big Data Analysis and IoT sensors thanks to powerful AI algorithms. This allows municipal officials to get a full picture of urban dynamics, predict issues, and adopt remedies proactively. As the Machine-Assisted Mayor trend takes hold, Finnish smart cities will be at the vanguard of a new age in governance. Human leadership combined with technical innovation produces a dynamic synergy, opening the way for a future in which cities are intelligently coordinated, reacting in real time to the needs and ambitions of their citizens.

Dator's second law of the future…

"Any useful idea about the futures should appear to be ridiculous."

(Dator 2019, 4)

> Recalling this quote by Jim Dator at the 2nd page of this thesis, which I first encountered in my early lectures during the beginning of my Futures Studies program. This quote has stayed with me since then. It's particularly relevant because even before I joined this program, I was working in local government, where I witnessed the gradual integration of technology into our public services. This experience reignited a fascinating concept in my mind: the idea of "AI-Mayor." Back then, the notion of AI-driven technologies replacing public officials and politicians might be seemed absurd, given the circumstances at the time. However, as of today, we find ourselves anticipating the concept of a "Machine-Assisted Mayor" with its unique capabilities.

Finnish SCDT applications are set to capitalise on these disruptive trends, resulting in a perfect combination of technical innovation, sustainable living, and community engagement. Eventually, ideal connected national DTs. Finland's innovation ecosystem is on the verge of a revolution that could change the future of cities and urban living and can establish new standards for the global urban environment owing to the meticulous integration of these innovative technologies.

3.2.10 MICRO – Niche Level Analysis and Findings

The informants provide essentials niche-level perspectives on the use and innovation of DTs in the context of Finnish smart cities. These viewpoints illustrate both obstacles and possibilities in the creation of Finnish SCDTs, as well as potential pathways for innovation.

One repeating issue is the necessity of data utilisation and cross-sector collaboration. The mention of GDPR difficulties and the necessity for procedures to promote cross-sectoral data collaboration points to a difficulty in realising the full potential of synthetic data production for DT applications. This gives an opportunity for innovation in establishing safe and privacy-preserving methods of sharing and using data across domains. Developing platforms or frameworks that allow for smooth data interchange while conforming to legal and ethical norms might be a lucrative niche.

Another major revelation is centred on the notion of "superpower" via data and AI integration. The combination of abundant data and AI-driven analysis represents a game-changing prospect. The idea of inhabitants and urban planners being able to visualise and shape their surroundings with the help of AI-generated scenarios is appealing. Innovations might focus on creating AI-powered tools and interfaces that allow individuals and experts to collaboratively visualise, model, and iterate on urban design proposals. The informants additionally address the concept of centralising points of access to streamline interactions and services. Streamlining bureaucratic processes and providing service access through a single point of contact coincide with the larger SC objective of improving efficiency and user experience. Innovations in this area might include the development of unified digital platforms that provide a variety of services, ranging from utility connections to permits while utilising DT technology to provide a comprehensive perspective of the urban environment.

Furthermore, the mention of AR and the role of VR glasses technology such as Apple Vision Pro or Meta Quest adds a new dimension. Integrating AR with DT data has the potential to transform urban planning and public participation. Develop AR apps that overlay DT simulations over the physical world, allowing real-time visualisation of planned modifications and advancements.

Overall, the findings indicate that the Ecosystem Agreements and high-ranked Finnish Start-up Ecosystem (NewCo Helsinki, 2021) have many windows of opportunity for novel DT innovations for **Smart-Ups** in Finnish city context:

- **Secure Cross-sector Data Collaboration:** It entails creating strong frameworks for sharing and using data across sectors while maintaining privacy and security.
- **AI-Enhanced Urban Design:** Developing AI-powered tools and interfaces that allow people and experts to envision and modify urban design proposals collectively.
- **Unified Digital Service Platforms:** Creating complete digital platforms that provide a one-stop shop for a variety of urban services, utilising DT technologies for

integrated insights. That plays a vital role in the development of the National Digital Twin platform.

- **AR Simulations:** Exploring the integration of DT simulations with AR apps to enable immersive and interactive urban planning experiences with shared future visions.
- **Predictive Analytics for Smart Infrastructure:** Using DTs and artificial intelligence to initiate prescriptive initially then ideally, create cognitive DT application for optimising autonomous infrastructure maintenance, energy consumption, and resource allocation.
- **Sustainability and Resilience:** Modelling and simulating the influence of sustainability programmes and resilience policies on the urban environment using DT applications.
- **Community Engagement and Education:** Developing interactive DT experiences that include individuals in the urban planning process while also providing educational insights to all stakeholders into the city's future growth.

These prospects are consistent with SC goals such as increased efficiency, sustainability, public participation, and quality of life. As technology advances and the potential of DTs becomes clearer, creative solutions in these areas might have a huge impact on the future of Finnish smart cities.

In addition to niche level analysis, **Interview Question 6** was asked to informants to ascertain if participants consider alternate possibilities if Finland's envisioned data-driven economy, as stated in the Digital Compass, finds difficulties. This inquiry is intended not just to elicit information about potential roadblocks, but also to identify possible solutions that could contribute to Finland's data-driven economy vision, as outlined in the Digital Compass and Ecosystems Agreements.

> **IQ6.** What if data-driven economy aspects don’t work, how can effective coordination, and alignment of cities and sectoral goals and priorities in smart city digital twin projects be ensured through new policies, frameworks, and collaborative approaches?

The findings highlight the importance of a vibrant data-driven economy in supporting efficient coordination, alignment of cities, and sectoral goals within SCDT programmes. The overall perceptions of informants are that failure to recognise data-driven characteristics can hinder innovation, inhibit niche-level developments, and result in undesired possibilities for economic growth and employment creation. Concerns about privacy, motivation difficulties, and the decline of competitive advantage might compound the problems. Furthermore, the lack of an effective data-driven strategy may jeopardise policy frameworks and regulatory changes, restricting the ability of SC projects to address urban challenges. Finally, the failure of data-driven economy features might deprive residents of the anticipated benefits of enhanced digital services, resource allocation, and general well-being, emphasising the necessity of strategic planning, collaborative efforts, and robust data-driven economy elements.

Several major themes emerge from the participants' perspectives, enlightening effective strategies for achieving coordination and alignment across SCDT initiatives. A reoccurring topic emphasises the need of policy formation and the creation of holistic frameworks. Respondents emphasise proactive policy development that establishes clear norms, standards, and goals, allowing for the smooth integration of data-driven techniques across varied cities and industries. Furthermore, there is agreement on the critical leadership role of cities in advancing these programmes. Participants emphasise the importance of localised decision-making, which allows cities to identify goals, foster collaboration, and guide the alignment of common objectives among many stakeholders. Integration is also emphasised as critical in numerous parts of municipal planning and procurement procedures.

It seems that data-driven concepts should be seamlessly integrated into urban development, infrastructure projects, and public services, according to experts, to ensure harmonic alignment with sector-specific goals. Collaborative approaches involving stakeholders, including corporations and citizens, are highlighted as critical, and incentives are suggested to encourage involvement. To foster trust and collaboration, robust data governance, privacy protection, and ethical data usage are thought critically.

An interesting and original notion is also discussed, during one interview session providing a potential relationship between a *universal basic income and data interchange*, a novel idea highlighting a universal basic income and data exchange combination with third parties’ platforms. Individuals provide their data in return for specific rewards or even basic income, matching individual motivations with wider overall data governance purposes, according to this forward-thinking concept.

In sum, respondents emphasise the importance of strategic planning and policy interventions in managing the complexities and problems associated with various stakeholders. Standardised frameworks and similar concepts are seen as essential for efficient coordination, establishing common understanding, and facilitating collaboration.

3.3 Research Limitations and Ethical Considerations

In the process of this research, some practical limitations were encountered. The most noticeable obstacle was the lack of IPRM case studies on SCs and DTs that could guide futures practitioner within the scope of future research. For this reason, five-stage IPRM phases were created by synthesizing the case studies provided in the guide source (Ahlqvist et al., 2012) and the research processes used by the authors for roadmapping. Another important factor was that the complementary iterative workshop approach of IPRM, which is sine qua non for consistent IPRM, could not be applied. Due to time and budget constraints, this research could not lead to iterative workshops that should have consisted of experts from different backgrounds. This gap has been tried to be closed with the comment round and the "Futures Cities" radar and trend analysis, which were used with special permission from the Futures Platform, as well as meticulously carried out desktop studies for each roadmap.

Comments round expert invitations were also limited. While the experts at cities and ministries relating on the policy context level of IPRM upon SCDT domain in Finland were contacted and easily interviewed, although many efforts were made for expert participation for the sectoral level of IRPM, and invitations were sent via social media and mail, unfortunately no positive response was received. As a result, objective data quality in sectoral supply-side systemic innovation policy insights expectations could not be met as it was intended in the early research planning phase. Due to the language barrier, some Finnish policy documents that might be significant for the objective of the research could not be interpreted. This limitation was tried to be overcome by referring to the English press releases of the relevant ministries on the internet and the case analysis and reports in the organization's official websites.

In general terms, both study constraints and ethical issues were explored in the investigation of the future of Finnish smart city digital twins. While insights were synthesised with literature and desktop study findings as well as interview insights, because participants were from larger cities such as Helsinki, Vantaa, Tampere, and Turku, the analysis may acknowledge potential sample bias, urging future research to include a broader range of Finnish urban and rural areas. While interviews and surveys provide information, the study prioritised participant confidentiality and open interpretation. While acknowledging context-specific findings, this study is wary of sweeping generalisations.

It is critical to recognise key futures research challenges inherent in this research when analysing the prospects of Finnish smart city digital twins. To begin, the participants from the cities in which they participated—Helsinki, Tampere, Vantaa, and Turku—might unintentionally restrict the range of perspectives on digital twin deployment across the larger spectrum of Finnish smart cities. Second, while primary data was gathered through interviews with mainly city and ministerial officials and technology experts, the possibility of response bias cannot be completely discounted, which might impact the stated perspectives on digital twin efficacy and problems in Finnish cities.

Furthermore, the findings are peculiar to the current state of Finnish smart city digital twins and could not be easily generalised to other nations or areas with distinct urban dynamics and governance frameworks. By recapping literature findings, it should be highlighted that every city needs, and their internal socio-technical dynamics are diverse, and every nation's visions and desired futures rely on their cultures, motivations, worldviews, and socioeconomic and political dynamics with available transformation resources such for technical innovations and specifications of SCDT developments.

Finally, the time frame of this study could miss the long-term implications of evolving policies, technological breakthroughs, or shifts in urban planning strategies, potentially impairing the accuracy of our assumptions about the trajectory of Finnish SCDTs. While these limitations are acknowledged, they contribute to improving the openness and dependability of the findings given in this study, as well as providing useful considerations for future research and practical applications in the realm of SCDT development in Finland.

Ethically, futures research should assure data credibility by continuously unfolding and evaluating policy and technological advancements. This explorative future research intended to give detailed insights into Finnish SCDTs while adhering to the principles of integrity and inclusiveness of anticipation in futures research. Exploring the future of Finnish SCDTs needs a strong knowledge of the ethical concerns that such study entails. The study concerns about representation and the potential lack of voices from less major metropolitan centres as well as city's socio-technical regime actors such as citizens as users, industrial actors, broad technology experts, communities as cultural aspects, and broad scientist with various backgrounds. To remedy this, future research should prioritise assuring an inclusive with multi-actor perspective and varied sample of cities to prevent perpetuating biases or omitting important viewpoints. Furthermore, the use of surveys and interviews with city officials and technology experts should highlight the need of maintaining participant anonymity and confidentiality.

Given the possible impact of response bias, efforts should be taken to report findings in a clear manner while minimising any unintended bias in their interpretation. This study's limited scope to Finnish context, ethical issues need an explicit acknowledgement that while findings were interpreted specifically for Finnish context and might not be universally applicable, advising researchers to avoid overgeneralization in cross-national comparisons. Yet, by empirically utilization of IPRM on SCDT, the thesis intended to provide an alternative holistic approach to the SCDT phenomenon and researchers might want to utilize on mitigating system complexities in their cities or national context. Concerns about data accuracy and dependability highlight the importance of meticulously verifying specifications from original sources to maintain the legitimacy of research analysis and findings.

4 Discussion and Conclusion

4.1 Synergizing Futures Studies and Smart City Digital Twins: Envisioning Resilient Urban Futures

This section revolves around the second research question.

> RQ 2: “How can Smart City Digital Twins be applied as testbeds for Futures Studies tools?

By “RQ 2”, this research also aimed to explore and evaluate the potential functions of Futures Studies tools within the context of SCDT applications and investigating how the successful integration and utilization of DTs in future smart cities can be enhanced and expanded by the capabilities of Futures Studies methods and tools.

A remarkable relationship is emerging in the ever-changing realm of urban development: SCDT applications and futures studies tools/methods. These fields, each with its own set of capabilities, are coming together to form a tremendous synergy that promises to transform the way we conceive, design, and create future of resilient cities. The data-driven innovation of SCDTs is at the core of this correlation. DTs, technical marvels, work ceaselessly to collect and analyse real-time data from sensors and IoT devices to present a vibrant and accurate perspective on the urban scene. Their ability to provide forecasting, predictive assessments, and scenario simulations opens the door to a universe of possibilities, one in which the future is scientifically built rather than speculated on.

Futures studies methods and approaches, a multidisciplinary field committed to exploring the mysteries of the unpredictable nature of alternative futures. Futures studies give an organised way to anticipate alternative future paths, with a strong emphasis on foresight, scenario development, and participatory future planning. Consider these technologies packed with dynamic data from DTs - a treasure mine of information that may bring life to future studies driven prospective strategies and roadmaps and give a tangible touch to strategic foresight research. The combination of these two can open an abundance of fascinating possibilities. To begin, the careful forecasting scenarios or what-if analysis generated by DTs may be validated and enhanced via the lens of futures studies. By including cultural, economic, and environmental aspects, the accuracy of these anticipates improves dramatically, providing decision-makers with unprecedented foresight.

With its capacity to simulate many scenarios and do what-if analyses, SCDTs open the way to inclusive and participatory future planning. Futures studies tools find a cyber ally here. As stakeholders and individuals interact with realistic digital visualisations, participatory scenario development, a cornerstone of futures studies, takes on new dimensions. A collective of voices helps to shape desired futures, cultivating a feeling of shared ownership in urban planning endeavours.

This cohesive partnership also benefits risk assessment and mitigation. Risks quantified by DTs, providing foresight practitioners with important insights into potential future uncertainties. Equipped with this knowledge, strategies for navigating uncertainty may be designed, giving future scenarios a solid advantage. Furthermore, this synergy results in a dynamic feedback loop. Futures insights strengthen DT models by providing a better knowledge of forthcoming trends and opportunities. The data-rich environment of DTs, on the other hand, informs and fine-tunes futures studies, enabling a continuous foresight refining process.

Having said that, the following **Interview Question 7** was evaluated for the opportunity to get insights of participants in various fields of expertise on SCDT due to the second research question.

> **IQ7:** If the Smart City Digital Twin applications are successfully integrated and utilized in smart cities, how can Futures Studies methods and tools such as scenario building, What-IF analysis and trend analysis be applied in them as testbeds? In your opinion, what kind of futures studies tools can navigate smart cities being more resilient for long-term challenges and how?

The interviewees had a varied but largely relevant understanding potential of futures studies. While the overall informants' insights imply futures studies approaches are recognised, it revealed that there is a lack of in-depth acquaintance in futures studies discipline. They see its potential use in SCDT's scenario development, future-informed analysis, comprehending dynamics of urban developments, and improving local planning and decision-making. Yet, there was a recurring theme of using futures studies approaches to address challenges, involve citizens, and contribute to smart cities' long-term resilience. The informants showed a common appreciation for futures studies integrated to DT strategies as an essential instrument in developing smart cities. They emphasised scenario development, what-if analysis, and real-time trend analysis as critical tools for anticipating urban issues and opportunities. Futures studies, with an emphasis on flexibility and community participation, are seen as a vital component of SCDT applications, according to the informants. Cities can handle uncertainties, make informed choices, and improve their long-term resilience in a fast-changing landscape and adopt shifting pressures on them by combining these techniques.

Incorporating methods and concepts from futures studies into the organisational and socio-political structure of city planning provides a multifaceted challenge. The perceptions of the informants illustrate the complexities required in negotiating these levels. Resistance to change within established structures and cultures, as well as the requirement for dedicated resources and cross-departmental collaboration, are examples of organisational barriers. The socio-political world adds further challenges, with altering political objectives and election cycles possibly influencing long-term futures studies programmes' commitment and longevity. Balancing the needs of short-term policy victories with the prospective visions of futures research necessitates a careful balance. Furthermore, closing the gap between desired futures and real policy implementation necessitates effective communication, capacity-building activities, and the establishment of accountability structures capable of accommodating the inherent uncertainties of futures. To address these problems, a deliberate effort is required to build an environment of support that values foresight, promotes cooperation, and guarantees that forward-looking insights from futures studies may seamlessly impact the dynamic terrain of urban government and planning.

Constructive discussions in this direction include the periodic use of foresight, cultural or organizational resistance and balancing socio-politic short-termism with long-term vision recalls the role of "Organizational Futurist", it is "[…] defined as a futurist working as a full-time employee for a single organization with responsibility for foresight activities." and "[…] an internal champion and broker to facilitate the integration process." in the context of DTs in smart cities (Hines & Gold 2015, 1). In this sense, organizational futurists who have mastered the philosophical and ontological knowledge of future studies and working on SCDTs:

- By integrating Futures Literacy (Miller, 2018) into the organizational culture, organizational futurists can play a vital role in making sense of the deliverables and tools that DT offer to cities and national officials for desired scenario construction, what-if analysis, or landscape trends within the framework of the cities or states' own dynamics.

- Organizational Futurist, however, would need to upskill a wide range of digital abilities to utilize DTs as testbeds for futures studies tools. The ability to create dynamic scenario feedback loop on desired futures requires proficiency in DT platforms, data processing, and visualisation. Understanding simulation modelling, basic programming, and local analysis improves the accuracy of scenarios. Knowledge of basics of cybersecurity, artificial intelligence, and machine learning improves scenario building capability while IT skill equipped futures practitioner can train DTs with new algorithms via prompt engineering enriched with futures studies concepts and assure ethical awareness on responsible use of citizen feedbacks for desired futures. These abilities would enable practitioners to investigate scenarios, analyse trend patterns, and provide intelligent suggestions to city administrators to promote informed decisions for resilient urban futures.

- Wide range opportunities of DTs would also add value to the development of digitalization of Futures Studies discipline such as real-time foresight and participatory scenario building approaches. This might be conceptualized based White et al.'s (2021, 5) online DT interaction diagram (See, **Figure 12**)

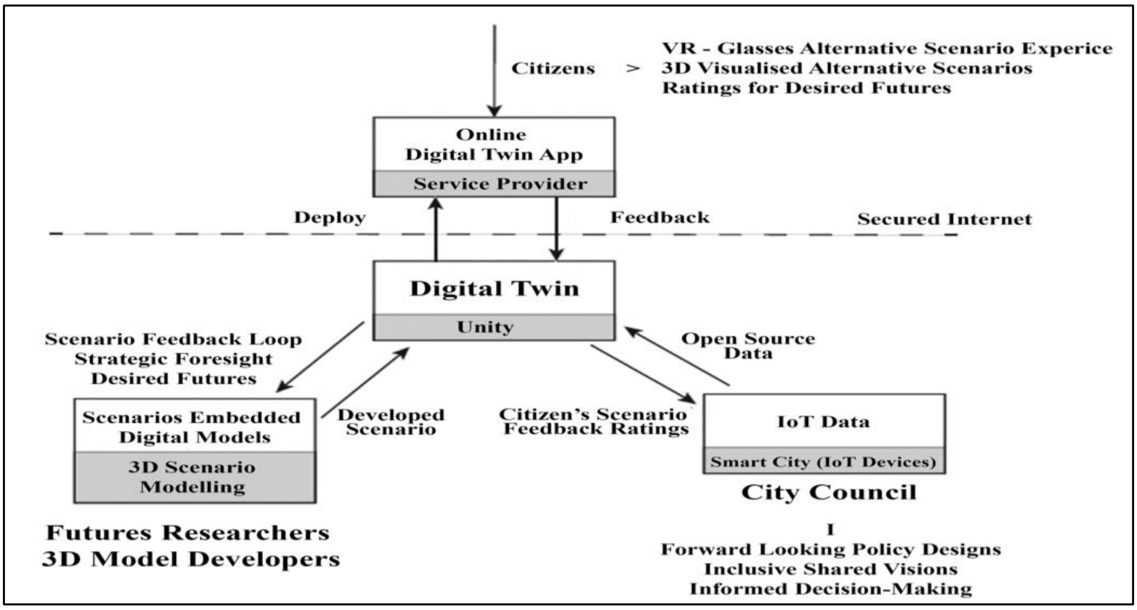

Figure 12. Real-time citizen-centric strategic foresight concept via scenario embedded digital twins (Modified from White et al. 2021, 5).

Based on this concept, the City Council wants to analyse the big data obtained from the Digital Layer Smart City applications for the future policy designs, integrate it into the Virtual Layer - DT application and get feedback from the citizens. Simultaneously, big data-based analytics, with the help of 3D model experts, allows futures researchers to integrate alternative scenarios based on trends, weak signals, and even wild cards (specifically related to the local or national context) into digital models and display them in online DTs. Citizens can determine their desired future with VR glasses, whether through DT feedback stations deployed in the urban pilot area or by sitting on the couch and examine alternative scenarios and providing simultaneous feedback with the rating system. The feedback from this can help the city council make informed decisions in a common vision based on desired futures and future policy designs, while future-researchers can both determine informed foresight strategies with real-time scenario updates and save their work from being a project-based product that specific stakeholders can make sense of.

Various informants' perspectives illustrate the potential synergy on foresight approaches in the research of merging SCDT applications with Futures Studies tools and methodologies. The importance of scenario planning, What-If analyses, and trend analysis in visualising and managing urban challenges was emphasised by the informants. However, obstacles remain at the organisational and socio-political levels, due to data complexity, local context differences, and a lack of multidisciplinary collaboration. Fostering data-sharing cultures, increasing stakeholder participation, and incorporating multidisciplinary fields of futures studies into DT development and nurturing forward-looking policy frameworks are some of the solutions.

To exploit the potential of DTs, organisational futurists should have a skill set that includes futures studies knowledge, data literacy, technological savvy, and collaborative abilities. By developing these skills, futures practitioners may simultaneously promote adaptation of futures studies development into fast-paced digitalization, improve long-term decision-making, and pave the way for adaptable and sustainable resilient urban futures.

4.2 Conclusion

This qualitative futures research delved into the complexities of SCDTs' socio-technical transformation in the Finnish context, explored their potentials to transform Finnish urban settings and foster resilient future Finnish SC development. The extensive literature analysis emphasised SCDTs' transformational capacity, offering light on their feasibilities in a variety of smart city dimensions as urban planning, infrastructure management, and public participation. The investigation highlighted the various benefits that SCDTs bring to the table, ranging from improved decision-making to optimised resource allocation, through a comprehensive analysis of current research investigations, interview insights and IPRM desktop study results.

Furthermore, the Innovation Policy Roadmapping (IPRM) used in the research provided a systematic framework for analysing and synthesising the complicated interaction of socio-technical regime actors' policies, innovative technologies, and desires in the context of SCDTs. The investigation gained useful insights into the challenges and opportunities inherent in the integration and utilisation of SCDTs within the context of Finnish SCs by including a varied range of experts during IPRM.

The IPRM process results and multi-level analysis of findings revealed a variety of actor-oriented policies, enablers, and forward-looking policies critical for realising SCDTs' full potential towards potential grounds for Finland Digital Twin Programme. Policymakers emerged as essential actors, particularly those entrusted with fostering a thriving innovation environment through incentive programmes, capacity and skill building, and new procurement methods in the face of challenges. The importance of collaboration across regime players, adherence to data standards, responsible technology development and usage such as AI, and data governance were highlighted. The technological roadmap, which was described as a subset of the transformation roadmap, highlighted the critical role of enabling technologies and “Smart-up” perspective within vibrant Finnish start-up ecosystem in driving the evolution of Finnish SCDTs, allowing for the coexistence of physical and virtual layers inside Finnish smart city systems.

The combination of SCDTs and Futures Studies methodologies might provide a revolutionary synergy with enormous promise for designing resilient urban futures. This research emphasised the significance of connecting technology innovation with strategic foresight to handle the complex difficulties that future cities might confront. As cities grapple with the challenges of rising urbanisation, technological disruption, and socio-technical landscape changes, the combined interaction of Smart City Digital Twins and Futures Studies offers a fresh path towards agile and sustainable urban planning. The study's contributions expand beyond Future of Finnish SCDTs, as it acts as an inspiration for the realisation of IPRM beneficial features for sustainable smart city transformations. While problems such as organisational resistance and socio-political dynamics persist, this research provides the groundwork for a future in which SCDTs efficiently integrate with futures studies approaches to traverse uncertainties and pave the way for adaptable and forward-thinking urban futures.

Given existing study constraints and ethical concerns, longitudinal futures research should give information on the long-term implications and impact assessments of SCDTs. Further extensive IPRM involving all participants in Finnish cities' socio-technical systems might provide various insights; consequently, future research should aim to explore multi-disciplinary cooperation and forward-looking policy implementation issues in the Finnish setting as well as future research should empirically consider the real-time citizen-centric strategic foresight concept via DTs. Finally, researching the function of high-level connected SCDTs in disaster mitigation, social well-being and urban resilience in Finland should be considered to support Finnish cities become safer and more resilient. These open issues contribute to the ongoing advancement of SCDTs as transformational instruments for building sustainable urban futures.

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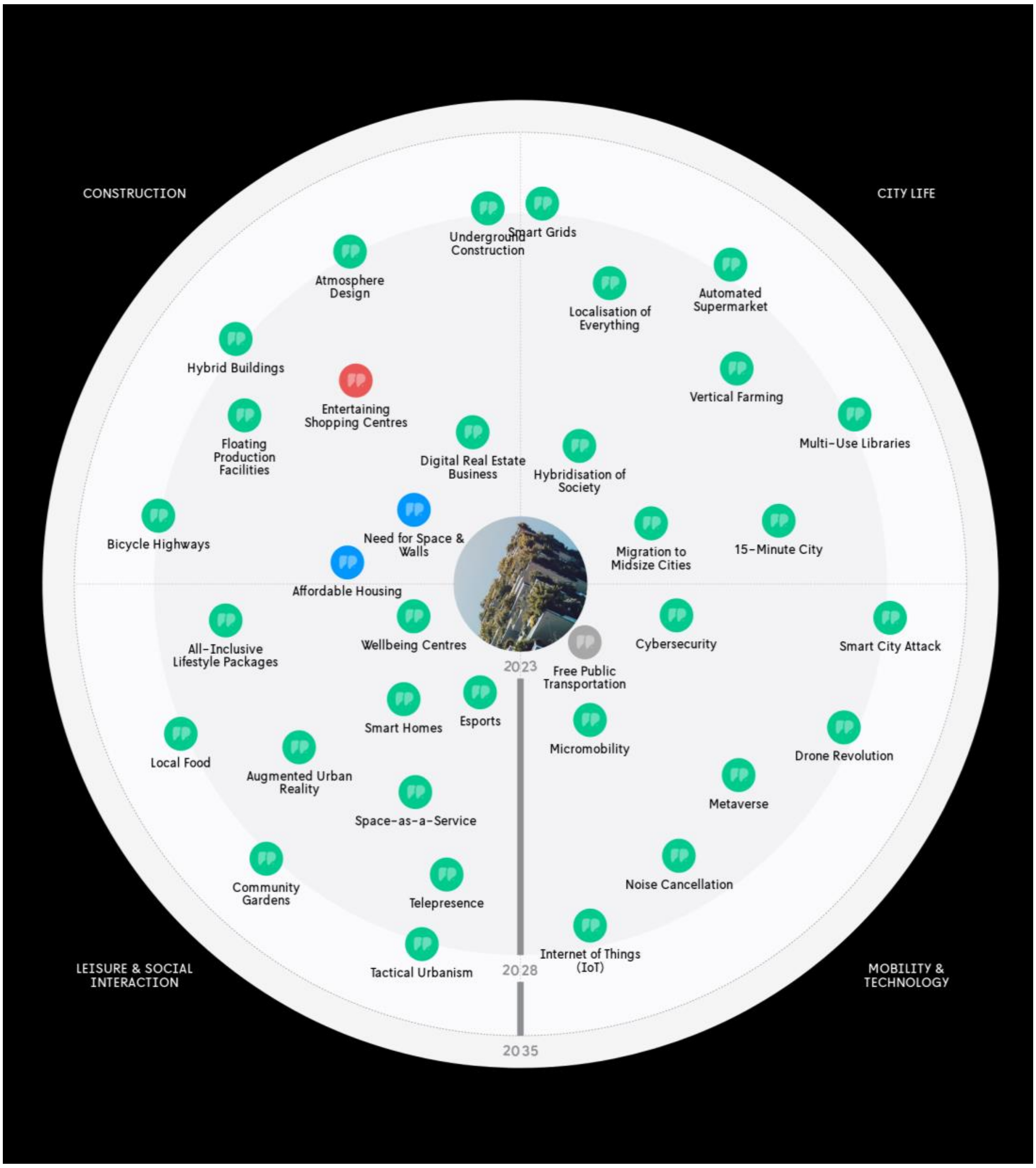
Appendices

Appendix 1 CDBB's Skills and Competency Framework: Professional Digital Twin talents, their essential tasks and required skills.

Resource: Skills and Competency Framework - Supporting the development and adoption of the Information Management Framework (IMF) and the National Digital Twin. (2021). Also available at: https://www.cdbb.cam.ac.uk/files/010321cdbb_skills_capability_framework_vfinal.pdf

Common Skills	**BUSINESS:** Transformational Leadership, Communication, Collaboration Adaptability, Commercial Mindset, Business Analysis **DIGITAL:** Lifecycle Assurance & Quality Management, Data Fundamentals Data Modelling, Analytics & Intelligence, Experience & Application, Security & Ethics	
Level	**Role**	**Task**
NATIONAL	**Benefit Manager**	Promotes and adopt an early benefits realisation culture and present tangible and quantitative benefits of sharing data for several different stakeholders and outcomes for the public good. They see benefits as new revenue generation, efficiency creation, the elimination of waste and the benefits of avoiding mistakes and disasters.
	Ontologist	Works to determine deeper logical structures and arrangements of information and understand philosophical ontology to meet the needs of the information management. Collaborates to define and develop national computational ontologies and data models for the built environment that facilitate integration / alignment with different ontologies.
	National Digital Twin Architect	A technical role needed specifically to build the information architecture. They are responsible for the aggregation and use of data sets specifically in relation to data interoperability and sharing at a national level between different types of organisations.
	Data Regulator	An independent authority set up to uphold information rights for the public good. They collaborate with regulated sectors, government bodies and other regulators to develop regulation that promotes openness, secure sharing, and data privacy for individuals - setting the framework for consistency. They are focused on the legal, cyber security and ethical use of data to drive national trust and transparency and ensure the nation benefits from availability and sharing of good quality data.
	Industry Leader	This individual helps to create and effectively communicate the strategic vision of the local and national level in a way that is applicable to the majority and easy to understand and cascade to others. This role takes the necessary opportunities for positive long-term change based on strategic priorities within the industry such as showing how data enables better decisions, empowering a culture that views data as an asset and makes everyone see they have a role to play in data quality.
	Policy Maker	Formulates and amends policy around data, spanning areas like privacy, sharing, ethics and security. They adapt and respond to industry needs as well as the public good. They aim to be supportive and quick at adapting policy to support innovation and development rather than hindering it. They see data as an asset and influence organisations to adopt the same mentality.
	Sector Regulator	Takes on an information planning role to identify information requirements for effective oversight of the sector. Works with process owners to understand the information needed at a sector level to support decision making. Collaborates with a variety of sector roles to define quality requirements and associated standard to facilitate sharing where necessary appropriate to meet those identified (and justified) requirements.
	Cyber Security Expert	Use technologies, processes, and controls to protect internet-connected systems such as hardware, software, and data from cyber-attacks. They also protect against the unauthorised exploitation of systems, networks, and technologies.
ORGANIZATIONAL	**Data Consumer**	Receives data to perform queries, analysis, and reporting for decision making. They must ensure that their consumption and usage of data complies with data governance and ethics policies as well as data sharing agreements. They also have stewardship responsibilities for identifying errors and issues in data and working with appropriate teams to rectify any quality issues.
	Data Custodian	Responsible for the aggregation, storage, and use of data sets. Deals with the actual nuts and bolts of transporting and storing data, rather than issues around what data is going into the system and why.
	Data Leader	Data Leaders inspire a shared vision on the benefits of data, seeing it as a defining asset in an organisation needed to meet strategic objectives. Promotes data as an asset and highlights the role everyone plays in improving data quality. Builds relationships and information exchange with external stakeholders to improve collaboration and knowledge sharing.
	Data Producer	Creates, updates, or deletes data in a system. Must understand how the data is defined, so that definitional guidelines and standards set by the organisation are followed. Usually responsible and accountable for the quality and accuracy of data they produce, whilst also adhering to legal compliance such as data privacy guidelines.
	Process Modeller	Process modelers are responsible for creating, sustaining, and improving a particular process within an organisation. They aim to create efficiencies, drive process quality enhancements, improve communication and promote correct adherence to the process.
	Data Architect	Plans and designs how systems relate to each other in a way that aims to integrate, centralise, protect, and maintain the systems and the data that resides in them. Ensures people have the right access to information in the right place, at the right time. Promotes data sharing and value through interoperability.
	Cyber Security Specialist	Use technologies, processes, and controls to protect internet-connected systems such as hardware, software, and data from cyber-attacks. They also protect against the unauthorised exploitation of systems, networks, and technologies.
	Benefits Manager	Promotes and adopt an early benefits realisation culture and present tangible and quantitative benefits of sharing data for several different stakeholders and outcomes for the public good. They see benefits as new revenue generation, efficiency creation, the elimination of waste and the benefits of avoiding mistakes and disasters.
	Enterprise Architect	Plans and designs how systems, processes, information, and roles relate to each other in a way that aims to integrate, centralise, protect, and maintain technology systems. Plays a major role in reducing complexity with digital transformation and establishes rules and processes around technology use whilst keeping up to date with trends and changing business needs.
	Data Governance Specialist	Responsible for overseeing the legal, ethical, and business compliance of data in relation to its availability, usability, integrity, and security. Enforces data standards and policies to control usage, sharing and quality to ensure data is consistent and not misused.
	User Researcher	This role is responsible for planning, designing, and carrying out research activities with users that help teams get a deep understanding of their users. This research informs proposition, service, content, and interaction design so that digital solutions work well for users.
	Business Analyst	Bridges the gap between the business and TI by understanding the technical options available based on user and business needs. Aims to improve adoption of technology and the quality management lifecycle. Analyses data to assess processes, determine requirements and suggest recommendations to stakeholders.
	Product Manager	Responsible for guiding the success of a product/system and leading the cross-functional team that is responsible for improving it, including understanding the people who are going to use the product/system and how well the product fits with the organisations vision and objectives. Co-ordinates the work done by other functions and takes responsibility for the development and adoption and of a product/service in the organisation.
	Process Owner	Accountable for the outcomes of a process and setting the direction for process modellers. They play a vital part managing and overseeing the design of a process and how it interacts with other processes. They set metrics to improve the process and effect positive change in relation to process objectives and business goals.
	Change Manager	Ensures projects (change initiatives) meet objectives on time and on budget by increasing employee adoption and usage. This person will focus on the people side of change, including changes to business processes, systems and technology, job roles and organisation structures.
	Data Quality Analyst	Monitors and examines the quality of data to ensure decisions are made using correct and sufficient information. They optimize the efficiency and quality of data collection, resolve data quality issues, and collaborate with others to make processes and technology convenient and suitable for ensure data is of good quality.
	Data Steward	As a primary advocate for data quality, helps to define data procedures, standards and guidelines and engage others in the quality management process. They understand how good quality data impacts value and shares this knowledge with others to encourage best practice.

Appendix 2 Futures Platform Radar "Future Cities: 2035"



Appendix 3 Transformation roadmap desktop study results

Full Desktop Study Results Info Pack available at:

https://drive.google.com/drive/folders/1YBLD3wf4V52CtrIG67fLXl6OAaPeoGds?usp=sharing

While you can access to the links of each resource, please share your comments on the same shared document on google drive page, and support this futures research, if you wish.

<table>
<tr><th colspan="4">TRANSFORMATION ROADMAP DESKTOP STUDY RESULTS</th><th rowspan="2">SOURCES</th></tr>
<tr><th></th><th>Present</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="13">Drivers</td><td colspan="3">Digital Inequality and Exlusion</td><td>EUROPEAN PARLIAMENT (2023) Social approach to the transition to smart cities.</td></tr>
<tr><td></td><td>Sovereign Cloud: Global uncertainty concerns over data privacy and potential government overreach, are resulting in greater demand for sovereign clouds.</td><td></td><td rowspan="3">GARTNER (2023) Gartner announces the top 10 governement trends for 2023.</td></tr>
<tr><td></td><td colspan="2">digital-native generation, demand has grown for mobile-first experiences that provide a host of various services with a user-friendly interface.</td></tr>
<tr><td colspan="3">ESG: Sustainable technology is an area that has risen to the top of priority lists for many company executives and should be looked at as a framework of solutions that increase the energy and material efficiency of IT services, enable sustainability of both the enterprise and its customers, and drive environmental, social, and governance (ESG) outcomes. Through the use of technologies such as artificial intelligence, automation, advanced analytics, and shared cloud services, among others, companies can improve traceability, reduce environmental impact, and provide consumers and suppliers with the tools to track sustainability goals.</td></tr>
<tr><td colspan="3">Sitra's 5 Themes: Nature, People, Power, People and Technology</td><td rowspan="2">SITRA (2023) Mega trends.</td></tr>
<tr><td colspan="3">Climate Change, Biodiversity Loss & Soil Degradation, The Dependency Ratio & Aging Population, Urbanization, Global Migration, Declining Trust in political decision-makers, Data Economy, Cyber Security, Digital Transformation and Upskilling</td></tr>
<tr><td colspan="3">European Parliament 6 Macro Challenges in Smart City Landspace:</td><td>EUROPEAN PARLIAMENT (2023) Social approac to the transition to smart cities.</td></tr>
<tr><td colspan="3">War for Talent: while technologies such as AI can do more with less manpower, more specialised professionals such as data scientists or engineers and architects will be needed to make sense of the abundant information.</td><td>PWC (2022) How digital twins can make smart cities better.</td></tr>
<tr><td colspan="3">A New Narrative for Human-Centric Smart Cities "Moomin Valley": We think that the technocratic models that aim to describe what smart city is should be replaced by normative narratives that define what good smart cities are like. We should focus on what the qualities of good governance of digital technologies for city organisations are – in other words, what is the character of a good smart city. the characteristics of cities described below are used to make technology the servant, not the master of people.</td><td>DEMOS HELSINKI (2020) People first: A vision for the global urban Age.</td></tr>
<tr><td>New Societal Norms: Consider behavioural analytics that form central part of today's business environment: technologies with long-term disruption potential emphasise both human and planetary-impact.</td><td></td><td></td><td rowspan="2">VTT (2023) Trend report 2023.</td></tr>
<tr><td></td><td>Generation Alpha (2010-2024)</td><td></td></tr>
<tr><td colspan="3">Finland's Digital Compass: Climate Change - Demographic Change - Geopolitical Chanve - Competition for Skilled Professionals - Emerging Technologies - New Business Operation Models. The accelerating climate crisis, an ageing and geographically concentrated population, the transformation of work resulting from digitalisation and new kinds of security threats in the digital environment are challenging governance structures and operating methods created over the last century. The sustainability gap in public finances to solve as the ageing of the population increases the number of senior citizens and creates pressure on health, care and pension expenditure and the decrease in the working-age population impairs economic growth opportunities. (Finland's Digital Compass)</td><td>FINNISH GOVERNMENT (2022) Finland's Digital Compass</td></tr>
<tr><td colspan="3">Net Zero Concept World</td><td>VTT (2023) Trend report 2023.</td></tr>
</table>

<table>
<tr><th colspan="4">TRANSFORMATION ROADMAP DESKTOP STUDY RESULTS</th><th rowspan="2">SOURCES</th></tr>
<tr><th></th><th>Present</th><th>Medium term</th><th>Long term</th></tr>
<tr><td rowspan="17">Sectoral Development: Solutions, Convergence, Disruptions</td><td colspan="2">Hyperautomations: According to Gartner, 60% of government organizations will prioritize business process automation by 2026, up from 35% in 2022. Hyperautomation initiatives support business and IT processes in government to deliver connected and seamless citizen services. CIOs must align automation initiatives with current priorities to pursue digital transformation, while also optimizing operational costs</td><td></td><td rowspan="2">GARTNER (2023) Gartner announces the top 10 governement trends for 2023.</td></tr>
<tr><td></td><td colspan="2">Digital Identity Ecosystems: Autorities faces new responsibilities in emerging digital identity ecosystems, with expectations to ensure trust, innovation and adoption across sectors and borders. To achieve this, governments must make high-assurance digital identity easy to obtain and relevant for diverse target groups of end users and service providers.</td></tr>
<tr><td colspan="3">digital ethics, responsible AI, human-centric computing, decentralized identity and homomorphic encryption. these technologies will be critical to facilitating the productivity revolution and the mainstream adoption of the smart world from both a societal trust and regulatory perspective. Strategic investment in those emerging technologies will enable tech providers to showcase their regulatory compliance and transparency in AI-enabled solutions, and enhance competitive product differentiation.</td><td rowspan="3">GARTNER (2022) Emerginng tech impact radar: 2023.</td></tr>
<tr><td></td><td colspan="2">Synthetic data derived by Generative AI will help train AI models where sufficient data is not available. There are already numerous areas that are taking advantage of synthetic data, including automotive, healthcare, finance, computer vision, data monetization, external analytics support, platform evaluation and the development of test data. Furthermore, synthetic data that is produced using generative AI techniques supports the accuracy and speed of AI delivery.</td></tr>
<tr><td colspan="2">Smart World: By 2026, key rapidly advancing technologies, such as digital twin, Internet of Things (IoT) platforms, smart spaces, multimodal UI and advanced virtual assistants, will transform how people interpret and interact with the world.</td><td></td></tr>
<tr><td></td><td colspan="2">Self-supervised learning will take us to the next phase of AGI - ASI by enabling data labels to be created from the data itself, without having to rely on external (human) supervisors that provide labels or feedback.</td><td>GARTNER (2021) Emerginng techonologies and trends impact radar: 2022.</td></tr>
<tr><td colspan="3">AI-TRISM: As artificial intelligence algorithms grow increasingly sophisticated and complex, leaders increasingly must bake governance, trustworthiness, fairness, reliability, efficacy and privacy into AI operations. AI TRiSM includes tools and processes that make AI models easier to interpret and explain while improving overall privacy and security.</td><td rowspan="2">GARTNER (2023) Top strategic technology trends 2023.</td></tr>
<tr><td></td><td colspan="2">Superapps: a composable application and architecture that provides end-users with a set of core features and access to independently created “miniapps” that allow for a consistent and personalized user experience within a single app.</td></tr>
<tr><td colspan="3">Transition from Industy 4.0 to Industy 6.0</td><td rowspan="3">BUSINESS FINLAND & AIF (2021) From industry x to industry 6.0.</td></tr>
<tr><td></td><td>Service Dominant Logic (SDL) of industries will be key elements on Industry 5.0 and Industry 6.0 approaches. The SDL approach will be linked to 3R sustainability strategy: Reduce, Reuse and Recycle.</td><td></td></tr>
<tr><td></td><td>Joint Test Factory</td><td></td></tr>
<tr><td>Adaptive Business Solution Collaborations changing current offerings to meet Future Smart City Interoperationality</td><td></td><td></td><td>MCKINSEY&COMPANY (2018) Smart cities: Digital solutions for a more livable future.</td></tr>
<tr><td>Data and platform-centric view of smart city developments</td><td></td><td></td><td>DEMOS HELSINKI (2020) People first: A vision for the global urban Age.</td></tr>
<tr><td colspan="3">Smartups Make Cities Smart There are four ways in which smartups circum- vent natural resource scarcity:
1. Through sharing, more value can be created with the same number of resources. Exam- ples: Airbnb and Sharetribe.
2. Applications can be used to optimise the use of a resource. Examples: Nest and Fourdeg.
3. Up-cycling, or tinkering with existing re- sources, can make the resources more energy efficient. Example: Pure Waste Textiles
4. Existing products and behaviours can be substituted with resource-efficient ones. Example: Solnet Green Energy</td><td>DEMOS HELSINKI (2015) Nordic cities beyond digital disruption.</td></tr>
<tr><td colspan="3">Smart City Marketplace - EC</td><td>EUROPEAN COMMISSION, Smart Cities Marketplace</td></tr>
<tr><td>EP's Smart City Guidance Tool</td><td></td><td></td><td>EUROPEAN COMMISSION (2019) Smart cities guidance package</td></tr>
<tr><td colspan="3">Smart Retro Model: Building the missing link through co-creation and testing</td><td>DEMOS HELSINKI (2015) Nordic cities beyond digital disruption.</td></tr>
</table>

	TRANSFORMATION ROADMAP DESKTOP STUDY RESULTS			SOURCES
	Present	Medium term	Long term	
Policies: Instruments and Regulatory Changes	Nordic Smart City Roadmap: boundaryless exchange of concepts and experiences, we can create new market opportunities for companies, new areas of research and development, and – ultimately – better communities for people to live in, today and for the future.			DEMOS HELSINKI (2021) The nordic smart city roadmap
		Adaptive Security: Gartner predicts that by 2025, 75% of government CIOs will be directly responsible for security outside of IT, including operational and mission-critical technology environments. The convergence of enterprise data, privacy, supply chain, cyber-physical systems (CPS) and cloud requires an integrated security approach. CIOs should link adaptive security to broader digital innovation, transformation, national security and resilience objectives.		GARTNER (2023) Gartner announces the top 10 governement trends for 2023.
		Cloud-Based Legacy Modernization: Leading governments are under pressure to break down legacy, siloed systems and data stores to modernize IT infrastructure and applications to ensure more resilient government services. CIOs can use adaptive sourcing strategies to identify areas where "as-a-service" delivery models augment internal resources and address business priorities.		
		Composable Policy Applications: demonstrates characteristics of composability have risen to the immediate challenges, improving overall business performance, reducing risk and lowering operating costs. Being composable means being able to extend the reuse of capabilities and continuously adapt to change. In government, that means being able to meet regulatory, legislative, and public expectations more readily and easily.		GARTNER (2022) What Government CIOs Need to Know About Composability.
	100 Ways to be Smart & Sustainable			SITRA, 100 ways to be smart & sustainable.
		R&D&I as drivers for a transition to (1) a sustainable, (2) human-centric and (3) resilient industry		Allied ICT Finland (2022) IoT next phase.
		Virtual Industry 6.0 University		
	"Green Ocean Strategies For Finland: To achieve this, Finland needs to be at the technological forefront of the world. The most important developments will take place in digitalization and auto-mation, e.g. 5G/6G-connectivity, AI (that will be especially exploited to be used in the intelligent network edge), autonomous systems, and the capability to integrate subparts into total systems. Finland is well known to be a global research leader in many of these areas, and academic-industry collaboration can ensure knowledge creation is embedded in the Finnish industry to the full extent."			
	DRGs - Digital responsibility Goals			
		Shift to user- and crowd-driven policy models of operations: Societal Development, Business Level and Technology Development (See Radar, Pg. 15)		
	Six-Policy Options for Future Smart Cities			EUROPEAN PARLIAMENT (2023) Social approac to the transition to smart cities.
	EU legislative frameworks and initiatives in the smar city domain of smar t transition and the risks tackled by them			
	Smart City Marketplace - EC			EUROPEAN COMMISSION, Smart Cities Marketplace
	Digital Europe Programme - EC			EUROPEAN COMMISSION, Shaping Europe's Digital Future
	Finnish and International Smart City & Digital Twin Standards CWA 17381:2019:en – The Description and Assessment of Good Practices for Smart City solutions ISO 37120:2018 Sustainable cities and communities — Indicators for city services and quality of life ISO 37122:2019 Sustainable cities and communities — Indicators for smart cities ISO 37123:2019 Sustainable cities and communities — Indicators for resilient cities ISO 23247-1:2021 Automation systems and integration — Digital Twin Series			ISO - INTERNATIONAL STANDARDIZATION ORGANIZATION & SFS - FINNISH STANDARDS ASSOCIATION
	SDG 11 - Sustaianable Cities and Communities			UN Department of Economic and Social Affairs Sustainable Development
	Human-Centric Smart City Governance: Unbounded, Vision-driven and Renegrative			DEMOS HELSINKI (2020) People first: A vision for the global urban Age.
	Gemini Papers: set the Centre for Digital Built Britain's vision for the future, showcasing the vital role that connected digital twins play in improving social, economic, and environmental outcomes, to create a better quality of life for all.			CDBB - Centre for Digital Built Britain (2022) The gemini papars.
	WEF - G20 Global Smart Cities Allieance Policy Roadmap			WEF - World Economic Forum, G20 Global Smart Cities Alliance
	Finland's Digital Compass			FINNISH GOVERNMENT (2022) Finland's Digital Compass
		European Interoperability Framework for Smart Cities and Communities		EC - National Interoperability Framework Observatory (2023)

Appendix 4 Technology roadmap desktop study results

Full Desktop Study Results Info Pack available at:

https://drive.google.com/drive/folders/1YBLD3wf4V52CtrIG67fLXl6OAaPeoGds?usp=sharing
While you can only access to the links of open sources, please share your comments on the same shared document on google drive page, and support this futures research, if you wish. Also, since Futures Platform is not open-source, if interested, you can reach out Futures Platform Team via https://www.futuresplatform.com/get-started.

TECHNOLOGY ROADMAP DESKTOP STUDY RESULTS				
Enabling Technologies	Key Technnology-based Solutions			AVAILABLE ONLY
	Present	Medium term	Long term	
Robotics, AI, IoT, Big Data Analysis, 3D Printing		Localization of Everyting: Enhancing smart supply chain resilience		FUTURES PLATFORM
AR, VR, 3D printing Hybrids of Things Hyper 6G Network Technologies		Hybridization of Society: Pushing forward a fusion of digital and physical worlds, creating a blended reality		
LED Light and Smart Nutrition Technologies		Vertical Farming		
Autonomous Technologies, Sharing Economy Services	15-Minute City			
	Micromobility			
Noise-bloking technology: acoustic metamaterials 3D Printing wireless IoT network-enabled microphones		Noiseless Cities: No noise pollution in cities mitigating the risks of residents' physical and mental health		
VR, AR, NFTs & Blockchain		Metaverse: where cities accomplishing their daily city services, and pelople accomplishing their work, studies and gain their income from there.		
Autonomous & AI-Supported Drone Swarms			Urban Air Mobility: Electric Vertical Take-off and Landing - eVTOL: Logistics, humanitarian aid in extreme areas, monitoring.	
		Airport City: multi-modal travel hubs that connect ground traffic and air traffic, tourists, local residents, businesses, and almost any services to form new types of hybrid areas. As urbanisation continues to accelerate rapidly and the aeroplane traffic grows, airports play a considerable role in enhancing regional connectivity, seamlessly integrating high-speed rails, flying taxi, autonomous shared vehicles, and hyperloops into existing transit chains		
NorrowBand-IoT Technology Cloud- and edge computing		Self-optimizing city public services ecosytems: smart grids and big data connected devices and platforms generate vast amounts of data that can be rapidly processed and analysed, providing detailed patterns and additional insight and foresight, enabling new solutions and item self-optimisation.		
Telepresence Technology: metaverse, mixed (MR) or extended (XR) reality, holograms, natural language processing with AI such as GPT, and the use of avatars		Ubiquitous City: cities access global, national and regional level expertise. Residents access local city and public services		
Gaming Technologies: VR, AR, video-streming	Esports City Centres, Esport City Hubs: Esport athletes, Esport Fans			
Ambient Technology, IoT, AI, Robotics		Smart home technology brings seamless city concept: personalised, automated, and adaptive experiences that suit residents' immediate needs		
AR, VR,	Augmented Urban Reality: a new digital layer to a urban space			
Sharing Economy Technologies and seamlessness		All-Inclusive City Lifestyle Packages & Leased Standard of Living		
Floating Photovoltaic, Wind, Wave Energy Grids		Floating Energy, Fishing, Sea-agriculture Farms: self-sufficient mini-ecosystems that work in symbiosis with the surrounding city, for example through circular economy. At the same time, they bring sustainable food production closer to the people of the city and serve as an educational and recreational destination.		
Hyperloop Technologies, cutting-edge underground construction technologies		Hybrid buildings resemble multifunctional mini-cities within actual cities		
			Three-dimensional smart city planning	
Decentralised smart grid Technologies powered by AI			Two-directional electricty flow among prosumer in city residents	
Digitalization, IoT, Cloud Computing			Smart City Attacks: Cybersecurity in transportation, health services, energy use, water management, waste collection, smart-buildings and security technologies	
			Smart and connected city countrysides	
			Forest Towns and Smart City Rurbanization	
			Biophilic Smart City Design	
			Tactical Urbanism: Citizen-led D-I-Y Urban Development	
3D Printing	3D-Printing Houses: Affordable City Housing			
Edge-Computing		Smart City applications that require real-time data; videos, facial recognition, virtual and augmented reality solutions, autonomous cars, and industrial processes are all examples.		
AI-IoT	Chatbots able to predict, identify, and solve problems and quite complicated questions in real-time in city services			

Available open-sources (also provided by the link for Desktop Study Results Info Pack)

TECHNOLOGY ROADMAP DESKTOP STUDY RESULTS				
Enabling Technologies	**Key Technnology-based Solutions**			
	Present	**Medium term**	**Long term**	
AVAILABLE OPEN-SOURCES				
AI	AI for Decision Making Intelligence: AI and data analytics investments will directly impact real-time operational decisions and outcomes. AI for decision intelligence provides governments with rapid, accurate and early decision-making capabilities at scale.			**GARTNER (2023) Gartner Announces the Top 10 Government Technology Trends for 2023.**
ANI-AGI-ASI		Digital twin adoption is expanding to help improve business decisions and outcomes via the visualization and support of smart robotic fleets, complex manufacturing operations and smart cities or even individual objects, like a car or a digital human.		
Smart Spaces	Low Touch Living			**GARTNER (2022) Emerging tech impact radar:2023**
Web3		Web3 is a new stack of technologies for the development of decentralized web applications that enable users to control their own identity and data. Technologies that are enabling this advancement and control include blockchain and tokens, which are creating new possibilities in how we manage digital trust, enable decentralization and execute transactions, as well as exchange value across parties. As the economy continues to digitalize, the need for digital mechanisms to manage, exchange and secure physical and virtual assets will only grow, driving demand for enabling Web3 technologies.		
Tokenization - Blockchain				
6G				
Collective 3D - IoT - Digital Twin			Metaverse that manifests from the combinatorial fusion of multiple technologies. A metaverse experience will enable the convergence of the physical and digital worlds in a persistent, contextualized and device-independent way.	
			Digital Twin as a Citizen	**SITRA (2023) Mega Trends.**
Quantum Computing	Transition from Industy 4.0 to Industry 6.0 Complex problem-solving & calculation - Optimisation & simulation (digital twins) - Risk modelling, defence, finite difference analysis			**BUSINESS FINLAND & AIF (2021) From industry x to industry 6.0.**
IoT, AI, Additive Manufacturing, Automation, Smart Factories, Cloud Computing, Logistics 4.0, AR-VR-MR, Big Data			Machine-assited Mayor	**VTT** **VTT City Tune - Smart City Guide**
	Transformative trends: Smart City Domains (Smart Cybersecurity)			**VTT (2023) Trend report 2023.**
Carbon Capture, Utilization and Storage Technologies		Decentralized City Energy production, transport, long- term storage, fuels, Industrial production, especially steel and chemicals		
Low carbon tecnologies				
Convergence of Internet of Things (IoT), cloud computing, artificial intelligence (AI), augmented reality (AR), edge, blockchain and other cutting-edge solutions		One-size-fits-all to Government for one: Tailored Public Services		**DELOITTE (2023) Tailored public services**
	Protect and connect with residents and businesses. Improve accessibility for all people in the community. Support businesses and fuel economic growth. Share information with the public. Streamline government operations. Deliver user-friendly community services. Provide reliable, intelligent infrastructure. Drive environmental sustainability. Promote cross-agency collaboration. Upgrade public transportation. Manage city resources to avoid waste. Collect and analyse open data to get valuable insights.			**MICROSOFT** **Smart cities: The cities of the future**
	CITY GRAPH - THE POWER OF DATA FOR SMART CITIES Siemens Advanta and Microsoft are working together to address your core challenges and developing City Graph - an Open Urban Platform, which supports digital models of urban design, providing rich context to enable the new generation of city applications. It is built on a cloud based open IoT platform, that connects all kind of devices and models the relationship between spaces, devices, and people in a graph. It utilizes Microsoft services including Azure Digital Twins, Azure IoT Hub, Azure Active Directory, ML and advanced analytics. The platform will offer cities the possibility to break through information silos and have for the first-time access to information put in proper context.			**SIEMENS ADVANTA** **City graph - The power of data for smart cities**
	Smart City Planning and Management Solutions: Integrated SCDT Solutions			**IBM** **Smarter Cites**
	Future SCDT Applications 2050			**PWC (2021) Smarter cities in 2050.**
	Bringing de-facto standards and Open Source to create a sustainable market of interoperable and portable Smart Cities solutions	Bad Hersfeld Smart City Case Exapmle: https://badhersfeld.urbanpulse.de/#!/tiles/environment.co,environment.dust_pm10,environment.dust_pm25,environment.humidity,environment.no,environment.o3,genericLighting,smartparking,trashbinsMrFill		**FIWARE**
	Smart Analytic App & Digital Twin Builder for Sentient Cities and IoT	Informative SCDT: Scenario and What IF Analysis Example: https://www.snap4city.org/dashboardSmartCity/view/index.php?iddasboard=MjE4Nw==		**SNAP4CITY**

Appendix 5 Interview questions and interview guide

Dear Researcher/Manager/Expert,

The purpose of this interview is to collect explorative data for a research study on Innovation Policy Roadmapping for the Future Smart City Digital Twins – SCDTs. The interviews will be separately conducted via Zoom Platform and before the day at which participant agree to join, the link will be shared with "personal" link and "login password". During the interview one semi-structed transformation roadmap and its background will be presented, and all the responses will be securely recorded for transcription, analysis, and reporting.
You are welcome to answer all questions freely and share your insightful thoughts and experiences.

Questions

1. How long have you been involved in smart city management, expertise, or research? Have you identified any policy or sectoral gaps in the feasibility and desirability of smart city digital twins?
2. In your view, what are the key challenges, opportunities, and strategies for effective implementation and scalability of smart city digital twins in the short and long term?
3. How do you envision smart city digital twins shaping the development of cities in the next 5 years and beyond, considering current trends and breakthroughs?
4. What are the most promising applications of smart city digital twins in areas such as environment, economy, government, citizens, living, and mobility?
5. Which emerging technologies or data sources hold the greatest potential to enhance the capabilities and functionality of smart city digital twins in the next 5 years and beyond?
6. What if data-driven economy aspects don't work, how can effective coordination, and alignment of cities and sectoral goals and priorities in smart city digital twin projects be ensured through new policies, frameworks, and collaborative approaches?

"Futures Studies" related question for participants:

7. If the Smart City Digital Twin applications are successfully integrated and utilized in smart cities, how can Futures Studies methods and tools such as scenario building, What-IF analysis and trend analysis be applied in them as testbeds? In your opinion, what kind of futures studies tools can navigate smart cities being more resilient for long-term challenges and how?

Participant privacy assurance:

- All information your provided will be handled with the utmost confidentiality.
- Personal information will be securely stored and used solely for the purpose of this study.
- Data collected will be anonymized and aggregated to ensure confidentiality.

Participant rights and voluntary participation:

- Participation in the study is voluntary, and you have the right to withdraw at any time without providing a reason.

Confidentiality in reporting:

- Findings and publications will only present analysed and aggregated qualitative data, ensuring individual identities remain confidential.

Conclusion

Thank you for your insights.
Are there other issues that you may want to address or comment on regarding this topic?
Do you know someone, an expert or professional in smart city or digital twins, who can provide some insights on this topic?

Thank you, once more, for participating!