

INTERIM DIGITAL TWIN PLATFORM STRATEGY SLOVAK REPUBLIC

FOREWORD

Since time memorial, Mankinds social interactions have produced communities around collective beliefs. Their convergence through trade and commerce, politics, religion or philosophical debate, have enabled the foundation of the first settlements. With population increase and human ingenuity, such settlements became towns; and towns became cities. We have continued to witness the evolution of cities, catalysed by the agricultural, industrial, technological and now digital revolutions: and this in turn has added greater complexity in the way we finance, procure, design, construct and operate our urban habitats.

Just as Mankind's evolving socio-cultural practices have transformed the places that we live, work, play, learn and relax; we are also witnessing transformations in the way in which we map them. Our shift from an analogue to a digital world has found expression in the way we represent our built environments. The hand-drawn, two-dimensional plans of our cities in the 19th century were revolutionised by the computerised, three-dimensional models of the 20th century: only for one technological advancement to be usurped by another in the 21st century. Herein lies the endless possibilities of the digital age, and its transformation on the built environment.

Digitalisation has enabled a far greater understanding of the world in which we live by the employment of big data: data that, when used wisely, can help shape our lives, and the places in which we inhabit. When mapping our urban habitats, "digital twins" provide a virtual mirror to our physical world. With this, they offer the prospect of testing and honing urban solutions before they become physical reality; heightening efficiencies and productivities, and with it reducing social, economic, environmental, spatial, cultural and technological risks. It would seem that the digital twin, as a virtual representation of the physical world, offers the prospect of more sustainable built environments.

This Digital Twin Playbook, authored by Pomeroy Academy for the Slovak Government, offers a new perspective by rethinking how socio-cultural practices found within the "social world, should be equally reflected alongside the natural and built systems of the physical world, in the digital (virtual) world. Only then can meaningful, quantitative and qualitative adaptations be made to our cities, districts, buildings and their landscapes that can enhance people's lives. In this digital age, a data-enabled society is the beneficiary to a complex interdependency between the hardware of the physical world; the software of the virtual world, and the 'heartware' of the social world.

We are proud to be part of this journey to digitally transform the Slovakian built environment through such a process; and trust that this Digital Twin Playbook will serve as the foundation for turning Slovakia's digital transformation into a reality and to plot the country's course to becoming a smart nation.

Prof Jason Pomeroy
Founding Principal
Pomeroy Studio

CONTENTS

FOREWORD	00	PART II: DIGITAL TRANSFORMATION IN SLOVAKIA	44
CONTENTS		DIGITAL TWIN FRAMEWORK FOR SLOVAKIA	44
EXECUTIVE SUMMARY	00	DEVISING A NEW MODEL FOR DIGITAL TWIN PARADIGM	45
FROM ANALOGUE TO DIGITAL CITY		8 REGIONS OF SLOVAKIA	45
SLOVAKIA 2030		RESEARCH METHODOLOGY	46
RESEARCH OVERVIEW		A PURPOSE-LED DIGITAL TWIN WITH 6 PILLARS	48
PART I: LITERATURE REVIEW		DATA LAYERS	50
BACKGROUND STUDY	10	SPATIAL	50
REASONS FOR CREATING A DIGITAL TWIN PLATFORM	10	ECONOMIC	52
DIFFERENT CONCEPTS OF DIGITAL TWINS	12	TECHNOLOGICAL	54
KEY STAKEHOLDERS INVOLVED IN THE CO-CREATION OF DIGITAL TWIN PLATFORM	14	ENVIRONMENTAL	56
KNOWLEDGE GAPS AND CHALLENGES IN EXISTING DIGITAL TWINS AND A DATA-DRIVEN SOCIETY	15	SOCIAL	58
COMPARATIVE ANALYSIS OF CASE STUDIES	20	CULTURAL	61
ANALYTICAL FRAMEWORK FOR COMPARATIVE ANALYSIS OF CASE STUDIES	20	4 SPHERES OF INFLUENCE IN SLOVAKIA	62
VIRTUAL SINGAPORE, SINGAPORE	24	PART III: ENABLING THE DIGITAL TWIN IN SLOVAKIA	
DIGITAL TWIN OF THE DOCKLANDS AREA, DUBLIN, IRELAND	28	A COMMON STATE / NATIONAL FRAMEWORK	66
DIGITAL TWIN CITY OF XIONG'AN NEW AREA, CHINA	32	SHORT-TERM 8 LONG-TERM GOALS	68
THE PLATEAU PROJECT, JAPAN	36	SCENARIO PLANNING	70
SUMMARY OF COMPARATIVE ANALYSIS OF CASE STUDIES	40	GLOSSARY	78
		BIBLIOGRAPHY	80
		APPENDIX	84

EXECUTIVE SUMMARY

FROM ANALOGUE TO DIGITAL CITY

THE REPRESENTATION OF THE CITY

The way cities are represented and understood has evolved significantly with social progress and technological advancement. The technologies brought forth by the first industrial revolution of the 19th century and the 4th Industrial Revolution of the latter part of the 20th century, have been reshaping human experiences at an individual level (Sacacas, 2020, pp. 4), as well as the way cities and urban infrastructure operate. As cities have become smarter, the advent of new technologies in the past century has influenced city planning and design, particularly in the representation of cities - from the prevailing hand drawings of the (analogue) city to programmable software products in the (digital) city. This has enabled different entities in the cities to behave in intelligent, coordinated ways (Moore, 2015, pp. 11; Metropolis Magazine, 2006).

As a pioneering example of hand drawn social cartography in the 19th century, Charles Booth's descriptive map of London poverty (Fig. 1), published in 1889, enabled analysis of the socio-economic dynamics and spatial structure of areas frequently stigmatised as ghettos (Vaughan, 2007, pp. 231). About half a century ago, hand sketched drawings (e.g. plans, sections, elevations) were still widely recognised as the dominant means for planning and designing cities, buildings and infrastructure. It was a standard practice to work in plan layers - each layer describing a different functional element of a site (e.g. city, district, neighbourhood), such as different land uses, circulation, and open space. Arduous data collection was made on-site and only updated intermittently, with the drawings based on abstractions that were understood primarily by those within the built-environment professions (Moore, 2015, pp. 12).

Despite the long standing history of the hand-drawn process, CAD drafting has been adopted as a replacement for two-dimensional (2D) drawings since the 1980s, and for three-dimensional (3D) isometric drawings over the last two decades (Coates et al., 2010, pp. 1037; Deniz, 2018, pp. 139). While the drawing representations have changed, the nature of information exchange has remained the same. However, the rise of information technology and the advancement of computer software and hardware have propelled the adoption of dynamic Building Information Models (BIM). As a collaborative tool, BIM has been largely used to support intelligent interrogation of design; enhance coordination of documentation; and improve communication between professionals involved in the construction process (Coates et al., 2010, pp. 1037).

TECHNOLOGIES AS ENABLERS TO CITY PLANNING

Standing at the intersection of urban challenges (e.g. waste management, pollution, and climate change-related catastrophes) in the 21st century, the adoption of technologies as enablers to solve those challenges has brought the planning of the city into a new dimension. This has manifested in combining 3D modelling with dynamic digital technology to create a Digital Twin (DT) city (Deren et al., 2021, pp. 1). By integrating with other systems of the cities, the DT city forms a new concept where smart cities can be built upon (Fig. 2). Assisted with Geographic Information Systems (GIS), activities within cities can be mapped to provide spatial and temporal data to DTs for visualisation, analysis, and prescribing city functions. (Moore, 2015, pp. 12-13).

It has become evident that the application of DTs for urban governance and planning has acquired a central place in recent years (Charitonidou, 2022, pp. 4) when smart urban interventions are growing rapidly. Therefore, it is of utmost importance to understand urban scale DTs from socio-technological perspectives and identify the knowledge gaps in existing DTs. This will, in turn, create breakthrough solutions to a more comprehensive, connected DT paradigm for the Slovak Republic as the young nation embraces s digital transformation.

2 a i i r i
i a a j

Fig. 1 Charles Booth's descriptive map of London poverty (Source: Booth, 1889)

Fig. 2 Digital Twin Cities (Source: World Economic Forum)

EXECUTIVE SUMMARY

SLOVAKIA 2030

A DIGITAL TWIN PARADIGM FOR DIGITAL TRANSFORMATION AS A YOUNG NATION

Marching towards the 2030 digital transformation (Fig. 3) journey, the digital twin technologies serve as the critical enablers as the Slovak Republic sets the goal of modernising the Slovakian economy and society with innovative digital solutions. The vision of the Slovakia 2030 digital transformation has been defined as follows:

"By 2030, Slovakia will become a modern country with innovative and ecological industry built on knowledge-based and data economy, with effective public administration ensuring smart use of the territory and infrastructure and with information society whose citizens use their potential at full and live high-quality and secure lives in the digital era."

- Ministry of Investments, Regional Development and Informatization of the Slovak Republic, n.d.

From the urban governance and planning standpoint, the digital transformation journey begins with the new spatial planning and construction law, resulting in the establishment of a central state administration body, namely the Bureau for Spatial Planning and Construction of the Slovak Republic (hereinafter the "Bureau for Spatial Planning and Construction"). The Bureau for Spatial Planning and Construction introduces the "Urbion" information system that can significantly contribute to the nation's digital transformation vision. "Urbion" is developed with the objective to improve efficiency in the electronisation and gradual automation of data-based planning and permitting processes. More importantly, it also lays the groundwork that ensures a common data environment where a national digital twin can be built upon.

The Digital Twin Playbook proposes a digital twin framework that encapsulates the spatial, economic, technological, environmental, social, and cultural aspects of the nation. To put the introduction of new legislation into practice, the digital twin, encapsulating the six pillars of sustainability (Pomeroy, 2014), will serve as the necessary impetus for launching Proof of Concepts (PoC), opening up more avenues for turning the Slovak's digital transformation vision into reality by 2030. Not only will the national digital twin improve efficiency and optimise resources of the Slovak Republic, but also enhance physical resilience and shape a future with positive outcomes for the Slovak citizens in the digital era.

Fig. 3 Digital Slovakia (Source: Ministry of Investments, Regional Development and Informatization of the Slovak Republic, n.d)

EXECUTIVE SUMMARY

RESEARCH OVERVIEW

This Digital Twin Playbook progresses through three main parts: 1. Literature Review; 2. Digital Transformation Progress in Slovakia; and 3. Enabling the Digital Twin Paradigm as a Nation.

PART I: LITERATURE REVIEW OF DIGITAL TWINS

Background Study: The Background Study is the first step to build an understanding of DTs across a few selected disciplines. This study is split into three parts: 1. the reasons for creating a DT platform (WHY); 2. the different concepts of DTs (WHAT); and 3. the key stakeholders involved in the co-creation of DT platforms (WHO). This understanding of DTs is followed by the identification of gaps in existing DTs, as well as the challenges of a data-driven society. This seeks to provide insights into rethinking the implementation of existing urban scale DTs that are designed for urban governance and smart city development.

Comparative Analysis of Case Studies: With the knowledge built up from the background study, an analytical framework is introduced and used to conduct a comparative analysis of case studies on urban scale DTs, ensuring an objective assessment is made for all cases.

The Literature Review concludes with a summary of comparative analysis of the selected urban scale DTs, posing a series of prompts for onward thinking that call for a new model of DT paradigm for Slovakia.

PART II: DIGITAL TRANSFORMATION IN SLOVAKIA

Digital Twin Framework for Slovakia: Developing a digital twin framework for Slovakia based on contextual relevance requires a thorough understanding of the digitisation process of the nation. Open data portals of the eight regions in Slovakia are identified and reviewed in order to understand the types of datasets that have been collected, as well as the data classification approach in each region. Subsequently, a six-pillar framework (Pomeroy, 2014) is introduced for developing a purpose-led digital twin for Slovakia. The six-pillar framework does not only encapsulate the broad range of datasets available in the on-going digitisation process across the eight regions, but also addresses the knowledge gaps identified in other existing urban scale digital twins that are largely lacking in the socio-cultural and economic aspects. This six-pillar framework involves the participation of stakeholders from the four spheres of influence (i.e. state, academia, industry, civil society), who will, in turn, benefit from the digital twin platform.

Data Layers: Having established an understanding that the data classification approach varies across different regions, the six-pillar framework is used as a common data classification structure, which can potentially streamline and standardise the digitisation process across the regions. The framework comprises six broad pillars - spatial, economic, technological, environmental, social, and cultural - that encapsulate different aspects of a sustainable smart nation. Each of the pillars is subsequently divided into six data layers and a set of indicators where different types of datasets can be organised accordingly. Diagrams are presented to provide a visual illustration of the components that make up each data layer in a sustainable smart nation.

Part II concludes with a list of stakeholders from the four spheres of influence that will form a strategic partnership in the digital twinning journey of Slovakia.

PART III: ENABLING THE DIGITAL TWIN IN SLOVAKIA

Enabling the Digital Twin Paradigm as a Nation: A common national framework is developed to enable a digital twin paradigm as a nation. The framework aims to align coordination across stakeholders from the four spheres who are wishing to participate in the digital twinning journey, from data collection to data sharing processes. Different levels of change and practices to be put in place by the stakeholders will be outlined (organised according to the four spheres), which will help to achieve the right level of data maturity and ensure data interoperability for the national digital twin.

Short-Term & Long-Term Goals: The common national framework is followed by the planning of short- and long-term goals, establishing the strategies for phasing out the national digital twin and ensuring immediate and long term benefits to the state, academia, industry, and civil society.

Scenario Planning: The scenario planning demonstrates a case where the workflow involves the four spheres - from industry to state, academia, and civil society - in which the entire workflow is optimised and made friendly by the digital twin. The workflow of each sphere is accompanied by diagrams and a step-by-step approach with reference to the data layers required: providing an overview of how the digital twin facilitates the four spheres in executing their respective desired task(s).

PART I: LITERATURE REVIEW OF DT

PART II: DIGITAL TRANSFORMATION
IN SLOVAKIA

PART III:
ENABLING DT

BACKGROUND
STUDY

COMPARATIVE
ANALYSIS OF
CASE STUDIES

DIGITAL TWIN
FRAMEWORK FOR
SLOVAKIA

DATA LAYERS

ENABLING A
DIGITAL TWIN
PARADIGM AS A
NATION

REASONS FOR
CREATING A DT
PLATFORM

ANALYTICAL
FRAMEWORK FOR
COMPARATIVE
ANALYSIS

DEVISING A NEW
MODEL FOR DT
PARADIGM

CATEGORISATION
OF DATA LAYERS :

NATIONAL
FRAMEWORK

DIFFERENT
CONCEPTS OF DT

VIRTUAL
SINGAPORE,
SINGAPORE

8 REGIONS OF
SLOVAKIA

4 SPHERES OF
DT
SLOVAKIA

SHORT TERM &
LONG TERM GOALS

KEY STAKEHOLDERS
INVOLVED IN THE
CO-CREATION OF DT

DIGITAL TWIN OF
THE DOCKLANDS
AREA, DUBLIN,
IRELAND

RESEARCH
METHODOLOGY

SCENARIO
PLANNING

KNOWLEDGE
GAPS &
CHALLENGES

DIGITAL TWIN
CITY OF
XIONG'AN NEW
AREA, CHINA

PURPOSE-LED DT
WITH 6 PILLARS

SUMMARY OF
COMPARATIVE
ANALYSIS

PART 1: LITERATÚRE REVIEW OF DIGITAL TWINS

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

REASONS FOR CREATING A DIGITAL TWIN PLATFORM

While the terminology of DT has arguably gained popularity in recent years, the technology itself actually has a long, enduring history (Qi et al., 2021, pp. 4; Singh et al., 2021, pp. 2). Scholars (Singh et al., 2022) identified 13 major industrial sectors where DTs have been extensively applied

in the midst of digital transformation. The four industrial sectors below are selected for further discussion, owing to a huge relevance in their operational efficiency and benefits, as well as ethical considerations, that can be drawn to smart city development.

Initial "DT technology was rooted in the aerospace and aeronautics fields, where the National Aeronautics and Space Administration (NASA) employed it as simulators to train astronauts and mission controllers.

Continuously serving as high-fidelity models, the simulators or DTs are designed and adapted to match conditions of actual spacecraft. Thus, the main applications of DTs in this field include:

- Optimising spacecraft's performance and reliability

- Modelling and prediction of failure scenarios for forensic analysis;

- Resolving failure scenarios with forecasts of results

- Making the missions safer for the crews

- Ensuring a higher probability of mission success

Different approaches of DT are applied in manufacturing while going through the four stages in the products lifetime.

Creation:

- Exploring product design iterations and resolving form-related conflicts virtually

- Gleaning insights from product data record (e.g. customers preferences and feedback),

- Optimising material selection based on cost, environmental impact, and physical properties.

Production:

- Resource management, production planning, and process control.

Operation:

- Monitoring products operation status and develop maintenance strategies accordingly

Recycling / Disposal:

- Supporting and improving product re-manufacturing based on product data record

DT applications in healthcare range from hospital processes to human organs or virtual patients.

Hospital Processes:

- Developing DT command centres, using simulation and prediction to improve hospital operations and patient care; optimising medical pathway planning; maximising surgical block schedule; designing new and existing facilities

Human Organs:

- Tailoring cardiological treatment to individual patients in a more targeted way

Virtual Patients:

- Predicting health issues and testing solutions to avoid or mitigate health complications, given the rise of quantified-self in terms of physical activity, sleep duality, heart rate, diet, weight, productivity, social interaction, and working environment.

Geographic and built contexts are potent to represent a city's assets or natural systems by bringing together data, reports, analyses, behaviours and different information models. This allows for sensing, analysing, predicting, and making informed-decisions according to citizens needs based on geo-locations. This leads to cities that are more sustainable in many ways.

Environmental:

- Managing and optimising resource supplies and consumptions to inform circular and net zero interventions

Economic:

- Evaluating trade-offs between resilience, efficiency, and cost.

Technological:

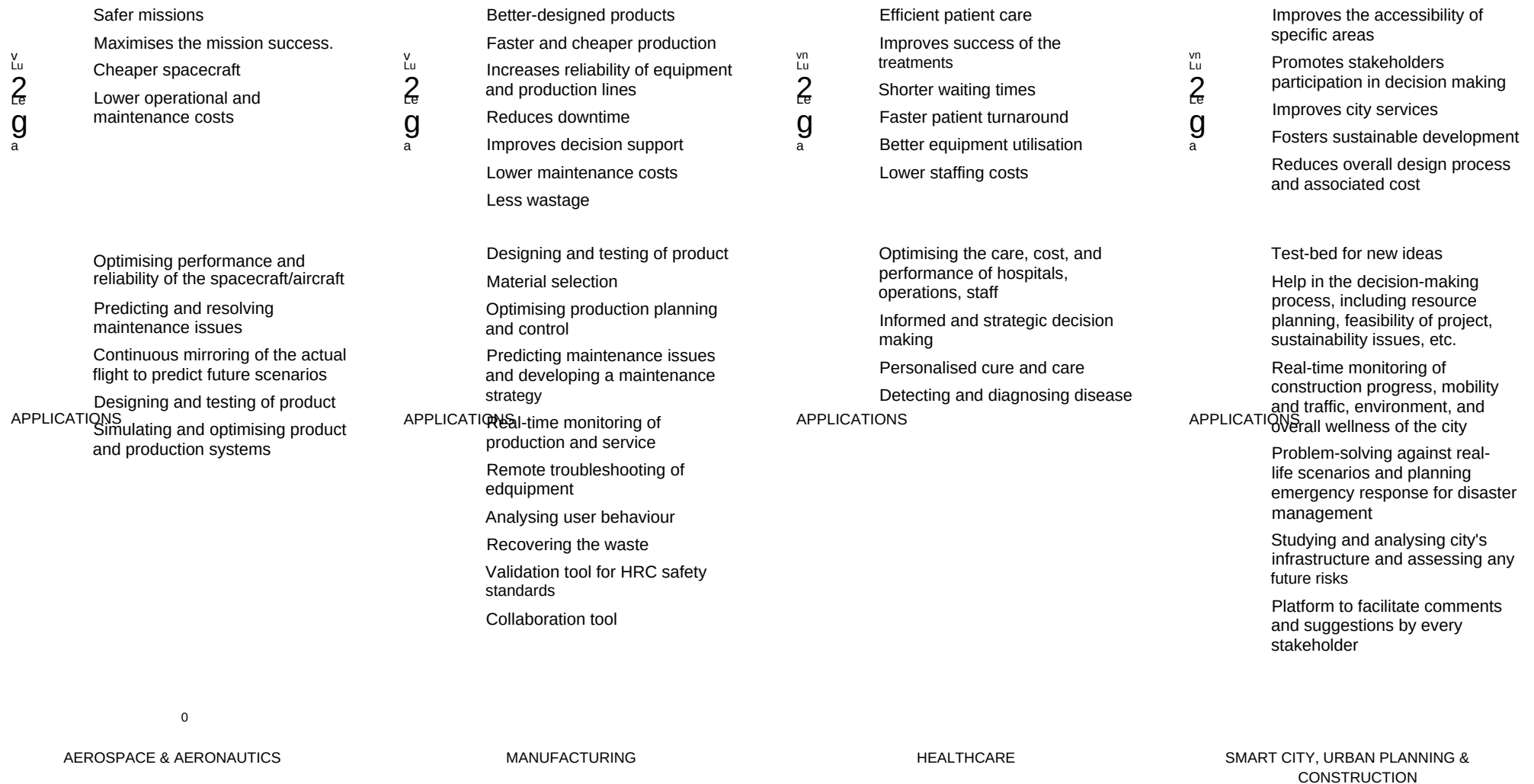
- Optimising data access to ensure decisions are made based on the best information available

Social:

- Facilitating democratic processes with a common platform for stakeholders' participation to inform better planning and design decisions

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

REASONS FOR CREATING A DIGITAL TWIN PLATFORM



LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

DIFFERENT CONCEPTS OF DIGITAL TWINS

The nomenclature of DT has changed over time. Nonetheless, the basic concept of DT has remained unchanged and invariably consists of three crucial parts: 1. physical entity, 2. virtual space, and 3. the connections tying them through information flow (Deng et al., 2021, pp.126; Grieves and

Vickers, 2017, pp. 93). Despite their similarities in these three parts, the nuances in the concepts of DT are found across different disciplines owing to their objectives and implementation.

In the aeronautics and aerospace area, a DT serves as a virtual instantiation of a flying vehicle. It is expected to experience every event that its flying twin experiences, supported by continuous statistical and physical testing in every aspect of a mission (Glaessgen and Stargel, 2012, pp. 10). Given the mathematical and physical emphasis in this field, a DT is defined as “an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.

@Glaessgen and Stargel, 2012

In the manufacturing industry, the physical product is tied to its virtual representation throughout the four stages of the products lifecycle — creation, production, operation, recycling / disposal. Hence, a DT is referred to as a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level.

@Grieves and Vickers, 2017

Considering its wide applications, the concepts of DT can be considerably varied within the healthcare sector.

Hospital Processes:

A DT is conceptualised as the digitisation of a hospital, a safe environment to test changes in system performance, allowing decisions and actions to be made objectively in terms of operational strategy, capacities, staffing, and care delivery models.

@GE Healthcare Partners, USA

Medical Practices:

A DT provides a “conceptual framework for analysing data-driven healthcare practices and the conceptual and ethical implications for therapy, preventative care and human enhancement”.

Virtual Patients:

A DT constructs “in silico representations of an individual that dynamically reflect molecular status, physiological status and lifestyle over time”.

@Bruynseels, Filippon, and Jeroen, 2018

A DT is generally defined as a virtual, dynamic, three-dimensional (3D) representation of the real world - including physical objects and systems between social, economic, and digital infrastructure, as well as the natural environment.

Centre for Digital Built Britain, 2022a; Esri, 2021; Mott MacDonald, UK

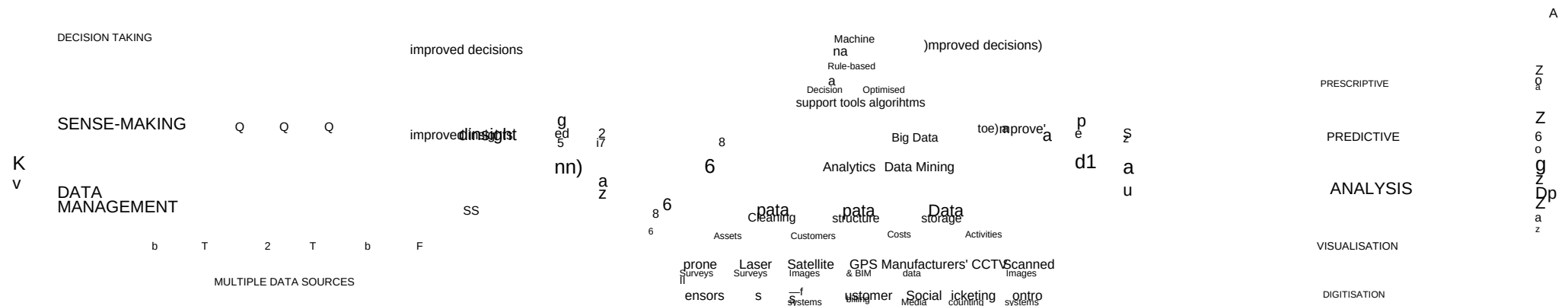
It is also known as a “collaborative data platform for virtual experimentation and test bedding”, using “technology and at the same time establishing bidirectional links with the physical world.

National Research Foundation, 2021; Stanford Engineering, 2020

Additionally, by going through the information value chain (Fig. 3), a DT can be seen as a far more efficient decision-making system, using a system of systems’ approach to understand inherent complexities of the elements within cities. This allows for system-based thinking while addressing systemic vulnerabilities in cities.

Centre for Digital Built Britain, 2022a

DIFFERENT CONCEPTS OF DIGITAL TW



"A digital twin is a digital representation of a physical asset, process or system. It is distinguished from any other digital model by its dynamic connection to the physical twin. A digital twin unlocks value by supporting improved decision making."

MOTT MACDONALD (U.

"Digital twins are realistic digital representations of physical things. They unlock value by enabling improved insights that support better decisions, leading to better outcomes in the physical world. What distinguishes a digital twin from any other digital model is its connection to the physical twin. Based on data from the physical asset or system, a digital twin unlocks value by supporting improved decision making, which creates the opportunity for positive feedback into the physical twin."

SMART CITY & URBAN PLANNING

ESRI (2021)

"Digital twins are virtual representations of the real world including physical objects, processes, relationships, and behaviours. A digital twin in a geographic context represents real-world assets or natural systems along with information models, data, reports, analyses, and behaviours in spatial context to the natural and built world. Digital twins may be used to represent the current, past, or even future state of assets. Digital twins mirror what exists in the real world today, but also can forecast what may exist in the future."

CHARITONIDOU (2022)

"Virtual Singapore' is a dynamic three-dimensional (3D) city model and collaborative data platform, including the 3D maps of Singapore...It will enable users from different sectors to develop sophisticated tools and applications for test-bedding concepts and services, planning and decision-making, and research on technologies to solve emerging and complex challenges for Singapore."

"Digital twin is a term used to refer to the digital representation enabling comprehensive data exchange and can contain models, simulations and algorithms describing their counterpart and its features and behaviour in the real world."

CONSTRUCTION

"A digital twin is a virtual representation of the world which enables us to use technology and at the same time establishes bidirectional links with the physical world."

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KEY STAKEHOLDERS INVOLVED IN THE CO-CREATION OF A DIGITAL TWIN PLATFORM

The understanding of DTs' applications and concepts has provided insights into the multi-scale, multi-functional, and interdependent complexities of the models, which require a strong integration and collaboration between government, academia, and industry (Centre for Digital Built Britain, 2022c, pp. 1). For instance, in smart cities, the multi-stakeholders collaboration, from the planning to implementation stages, includes state and local governments, ICT (Information and Communication Technology) service providers, transportation industries, energy and water suppliers, building developers, regulators and city operators; and finally citizens at the post-project evaluation stage (World Economic Forum, 2022, pp. 25-26; Esri, 2021, pp. 5).

The existing digital twinning process can, therefore, be evaluated as a co-creation process of strategic partnership primarily between (adapted from Pomeroy, 2020b, pp. 202) (Fig. 5):

1. State and local government - to regulate and govern the twinning process and smart city development;
2. Academia - to research and develop state-of-the-art technologies and digital innovations; and
3. Industry - to champion / co-fund "proof of concepts" while providing services to the cities.

This strategic partnership represents a series of expert inputs and discourses that span across sectoral boundaries and eventually enact them in practice in the digital equivalents (building on Solman et al., 2022, pp. 273; Jasanoff, 2004). In other words, the twinning decisions collectively hold consequences for what objects and systems are included and excluded in the DT, which in turn create a greater collective societal benefit in the physical twin (Centre for Digital Built Britain, 2022b; Fuldaer, 2019).

According to Centre for Digital Built Britain (2022c, pp. 1-6), a successful strategic partnership is premised on the:

1. Right culture – to foster strong leadership, collaboration, and improvement across government, academia, and industry;
2. Right values and ethics – to deliver genuine public benefit in perpetuity;
3. Right delivery vehicle — to coordinate and align between stakeholders and foster extreme collaboration through a top-down bottom-up approach; and
4. Right resources - to be developed in the open with ongoing community feedback to ensure they are useful and adoptable.

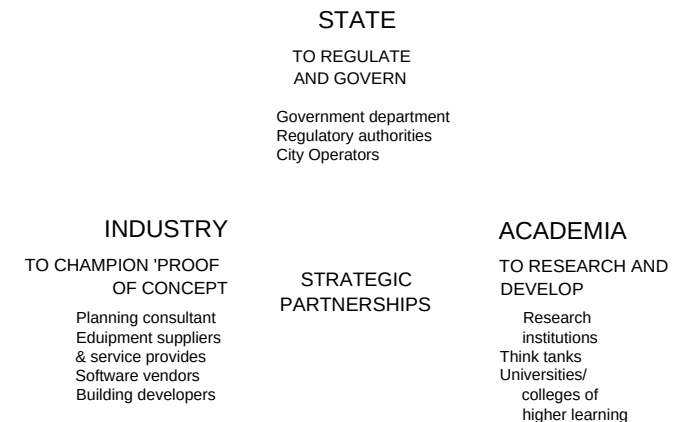


Fig. 5 Strategic partnership model of existing digital twins for urban governance
(Source: adapted from Pomeroy, 2020b, p. 202)

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KNOWLEDGE GAPS AND CHALLENGES IN EXISTING AND DATA-DRIVEN CITY

Stanford Engineering (2020) has identified two significant problems that are yet to be explicitly addressed by many implemented DTs:

1. There is a need for a “sustained top-down and bottom-up leadership to discuss and prioritise opportunities in order to fully realise the benefits of a DT
2. The existing DTs have widely adopted a ‘product-focused approach.

SUSTAINED TOP-DOWN AND BOTTOM-UP LEADERSHIP

Similarly, the Centre for Digital Built Britain (2022c, pp. 2) stresses the need for adopting a middle-out approach by bringing together specialist-led top-down and community-led bottom-up approaches in enabling an ecosystem of connected DTs for urban governance. While the former helps to ensure a strong strategy and route to comprehensive master plans, the latter allows practitioners from relevant fields to highlight knowledge gaps in solving real-life problems that are pertinent to cities.

Pomeroy (2020b, pp. 202) goes further to highlight the four spheres of influence that can form strategic partnerships (Fig. 6), with greater emphasis on perceiving civil society as an equally important stakeholder. Their equitable contributions to the process, can yield value to the eventual product (in this case, the DT), which are currently missing in most existing DTs. Such a strategic partnership with a “middle-out approach will ensure a level of sustainability essential for long-term city development and urban governance (Centre for Digital Built Britain, 2022c; Stanford Engineering, 2020; Wataya and Shaw, 2019).

It is apparent why certain scholars are emphasising the need of adopting a middle-out approach in urban scale DTs (Centre for Digital Built Britain, 2022c, pp. 2; Stanford Engineering, 2020; Wataya and Shaw, 2019). However, the intangible knowledge and values that could be brought particularly by bottom-up led approaches are challenged by pressures to tangibly demonstrate its capability of creating spillover positive outcomes and impacts on their beneficiaries (Wataya and Shaw, 2019, pp. 107). Despite existing efforts in enhancing citizens participation in the decision-making processes of urban planning strategies, questions are raised on to what extent the use of DT can contribute to achieve such an objective. This is due to two reasons (Charitonidou, 2022, pp. 12):

1. The creation of urban scale DTs is based on a limited set of variables and processes; and
2. The ways in which they abstract sets of variables and processes neglect the social aspects of urban contexts.

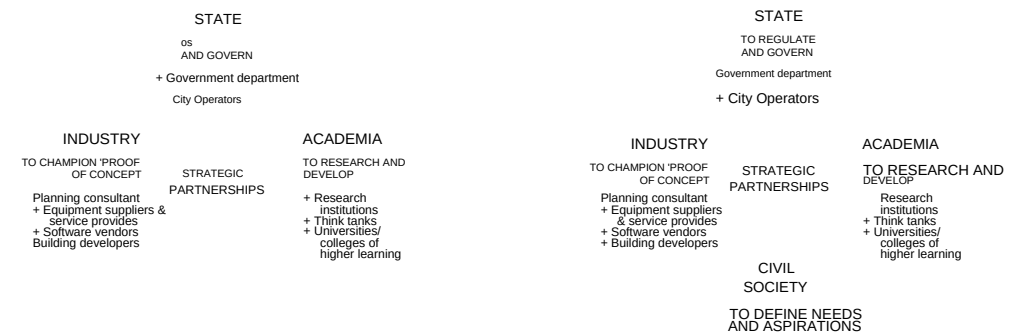


Fig. 6 Strategic partnership model (Source: Pomeroy, 2020b, pp. 202)

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KNOWLEDGE GAPS AND CHALLENGES IN EXISTING AND DATA-DRIVEN CITY

PRODUCT-FOCUSED APPROACH

Charitonidou (2022, pp. 4-5) suggests that the potential of urban scale DTs mainly comes from their capacity to monitor activities in the city, utilising the data collected via monitoring to shape more efficient and sustainable design solutions. However, the trends of building a data-enabled society has led to smart approaches that are “largely ignorant of people and what relates to them, consequently, contributing to the product-focused approach found in most urban scale DTs.

Speaking of the entities that relate to people, Batty (2018, pp. 819) remarks that “one of the quests in city modelling is to merge social and economic processes with the built environment and to link functional and physical processes to socio-economic representations’.

Likewise, Wataya and Shaw (2019, pp. 107) point out the significance to not only improve efficiency from bricks and mortar infrastructure (hard assets) and basic services, but also to deliver the intangible benefits (soft assets) that ensure the welfare and well-being of citizens (Fig. 7).



Fig. 7 Hard and soft assets that support city functions

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KNOWLEDGE GAPS AND CHALLENGES IN ~~EXISTING~~ DATA-DRIVEN CITY

PRODUCT-FOCUSED APPROACH

Human interactions play a vital role in defining the “social world in which people engage - they allow like minded individuals to create groups and communities bound by ethics, social contracts, laws and the codes of civil society. Social interactions then have the ability to shape the places, buildings, and infrastructure which take places in the physical world (Fig. 8). Such a place reflects, and is formed by, day-to-day life; traditions, and cultural practices.

In the digital-enabled society, digital technologies have since been adopted to model the physical world and create what is known as the virtual world. This results in the emergence of the digital twin, serving as a predictive tool to enhance performance in the physical world, but is often devoid of connection to the social world. As remarked by Charitonidou, 2022 (pp. 5), the data-driven approach in urban governance and the informed decision-making process, using a digital twin, often neglects the importance of the soft assets — “social interactions, social norms, culture, history, democracy, politics, human rights, ethics and essential non-material qualities, laws and regulations - that are essential in supporting city functions.

For the virtual world to be successful, it would seem essential for the digital twin to learn of the practices found within the social world in order for meaningful adaptations to be made to the physical world that can enhance people's lives.

DIGITAL

PHYSICAL

SOCIAL

Services

Use

Fig. 8 Socio-cultural practices are needed to effectively integrate social, digital and physical spheres

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KNOWLEDGE GAPS AND CHALLENGES IN
EXISTING AND DATA-DRIVEN CITY

BEYOND THE TRIPLE BOTTOM LINE: 6 PILLARS OF SUSTAINABILITY

In Cities of Opportunities, (Pomeroy, 2020a) elucidates the (six pillars' (Fig. 9), encapsulating both the hard infrastructure and soft assets, that are inextricably linked for the design and implementation of more smart and sustainable cities in the future.

Establishing the gaps in existing DTs further underscores the importance of going beyond the often accepted triple bottom line of social, economic and environmental; and expand upon this to include spatial, cultural, and technological considerations as equally vital parameters in the creation of DTs. After all, 55% of the world population reside in urban areas and this is projected to exceed nine billion people by 2050. This has consequently led to the privatisation of space and the depletion of those environments that once fostered social interaction. The continued flow of migrants and refugees seeking prosperity and security has resulted in cities becoming more heterogeneous and multicultural; and the shift from manufacturing to knowledge-based economies is being made possible through digital technologies that are revolutionising the way cities are planned, developed and governed. With DTs becoming essential urban planning tools propelling smart city progress (Zhang et. al, 2021), it is crucial that cities embrace DTs to go beyond the integration of ICT, to leverage social capital (Caragliu, Del Bo and Nijkamp 2011) and spur citizen participation (Peek and Stam 2016). Ultimately, DTs should endeavour to address and deliver social, spatial, environmental, technological, cultural, and economic outcomes to transform cities to become smarter, future-proofed, and more inclusive.

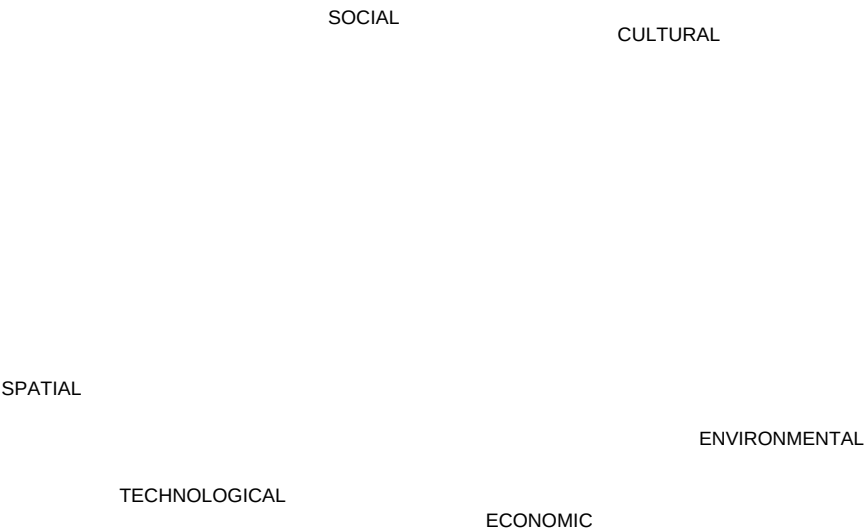


Fig. 9 The six pillars for sustainable cities of tomorrow (Source: Pomeroy, 2011)

LITERATURE REVIEW OF DIGITAL TWINS | BACKGROUND STUDY

KNOWLEDGE GAPS AND CHALLENGES IN EXISTING AND DATA-DRIVEN CITY

5 PILLAR 1: SOCIAL

The concept of social sustainability covers a diverse range of societal issues that broadly calls for greater equality amongst mankind. This lends itself to fostering greater liveability prospects for all regardless of gender, race, age, sexual orientation; better health and well-being, community engagement and increasing social capital. The legislative mechanisms of ensuring social support, human rights, labour rights, social responsibility and social justice similarly depend upon the relationship between people and the environment in which they occupy; and in these terms, social sustainability encompasses all human activities and should be read in conjunction with spatial sustainability.

4 PILLAR 2: SPATIAL

Space is a commodity in need of preservation and replenishment, yet continues to be depleted through urbanisation. One feels conscious of this in high-density environments such as Hong Kong – whether one experiences the confines of a micro-apartment or simply shares a table in a restaurant that has been ergonomically attuned to cater for multiple strangers dining at any one time. Space and society are intrinsically linked, and one cannot have a discourse about society and the way people interact without also discussing the space in which they can do this. Spatial sustainability as a counterpoint to social sustainability seem inseparable and key to the success of our future urban habitats as we seek to replenish the loss of space for society's interaction.

9 PILLAR 3: ENVIRONMENTAL

The concept of an environmental sustainability considers the needs of the planet as an equally important dimension to the needs of its people. Healthy ecosystems provide vital goods and services to humans and other organisms and this necessitates the reduction of the negative impact of humans on our ecosystem. There is the need to preserve and manage our environment for present and future generations largely based on environmental science and conservation biology. There is also the need for a cultural step change in the way mankind consumes via conventional practices, necessitating new "circular" ways of thinking that treats waste as a "flaw"-providing opportunities for products to be given a new lease of life. "Reduce, Reuse, and Recycle" is increasingly being joined by the further "Rs of 'Refuse and Repurpose', through a heightened environmental consciousness.

ii PILLAR 4: TECHNOLOGICAL

Technology has created as many questions as it has answers, yet society's continued and increasing use of it often means many technological advances and innovations have become ubiquitous in the way that we conduct our daily lives. Numerous studies of the social and environmental impacts of new technologies on society show that the effects of a technological innovation depend not just on the inherent characteristics of a particular technology but also on the way it is perceived, used or its ability to transform the context. An appropriate technological sustainability that acknowledges small-scale, energy-efficient, environmentally-sound, people-centred approach, can permit more community-focused activity to work in symbiosis with city-wide technological interventions.

PILLAR 5: CULTURAL

Cultural identity is increasingly challenged by globalisation. Whilst technology has helped bring people together and promoted the cross-fertilisation of cultures, innovations and ideas, it has also arguably contributed to a transcendence of modernisation and commercialisation that need not relate to people, place or culture. Spaces, which may have once been imprinted by cultural practices and time-tested rituals, are also being compromised through the process of urbanisation, which potentially undermines the cultural identity of a place. If globalisation means globalising modernity, and modernity represents the harbinger of identity, cultural sustainability may be strengthened in its ability to form a localised counterpoint to globalisation.

I PILLAR 6: ECONOMIC

The concept of economic sustainability refers to the economic well-being and quality of life of a nation, region, local community, or an individual that is improved according to targeted goals and objectives that do not compromise the needs of the People or the Planet. This translates to greater fiscal conscientiousness and a more acute understanding on societal value as opposed to societal cost. It can therefore be seen that an economic sustainability can correlate to the health and well-being of a nation or a business, and necessitates a fiscal prudence to remain in power, or in business. As more and more sustainable projects match public demand and government mandates, it has become increasingly important to ensure that sustainable processes deliver more economically sustainable products.

LITERATURE REVIEW OF DIGITAL TWINS | COMPARATIVE ANALYSIS OF CASE STUDIES

ANALYTICAL FRAMEWORK FOR
COMPARATIVE ANALYSIS OF CASE STUDIES ON URBAN SCALE DIGITAL TWINS

A city is like a network of systems - it is shaped by its people, influenced by the interactions between its people and the surrounding physical and non-physical objects related to them, and expressed by its people from a diverse background through collective intelligence and strategic partnerships overtime. Building an urban scale DT (virtual representation) is equivalent to the collective effort in building a city (physical representation). More importantly, it is essential to perceive an urban scale DT as a (purpose-led technology' instead of "technology-led change (Centre for Digital Built Britain, 2022b, pp. 7). This justifies the need to draw parallels between urban scale DTs and the strategic partnerships between the four spheres in the urban governance and planning process, from multi-source data collection to post-decision processes, ensuring the process is not automated by replacing the strategic partnerships and neglecting the soft assets of cities.

By adapting the information value chain pyramid (Fig. 4) (Centre for Digital Built Britain, 2022a, pp. 4; Mott MacDonald, UK, pp. 3), as well as the strategic partnership model (Fig. 6) (Pomeroy, 2020b, p. 202), an analytical framework is developed (Fig. 10) and used to objectively facilitate the comparative analysis of case studies on urban scale DTs. Besides, the different data layers gleaned from the case studies are categorised into the "six pillars" (Fig. 8) identified by Pomeroy (2020a, pp. 2-3), which are intrinsically linked parameters to represent urban systems complexities and to ensure sustainable cities. In response to the knowledge gaps and challenges identified, this comparative analysis provides an understanding of the extent of stakeholders involved in the processes and the extent of complexities of an urban system represented in existing urban scale DTs.

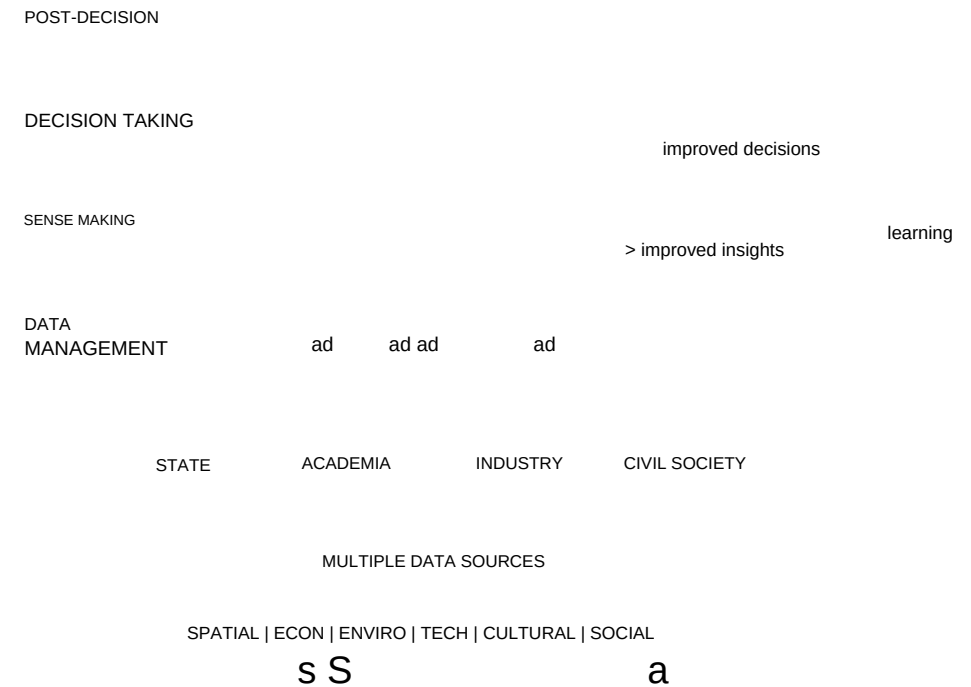


Fig. 10 Analytical Framework to facilitate comparative analysis of case studies on urban scale digital twins (Source: Authors).

LITERATURE REVIEW OF DICITAL TWINS | COMPARATIVE ANALYSIS OF CASE STUDIES

ANALVTICAL FRAMEWORK FOR OENVRNMENTAL ANALYTICAL TWINS

PO

a

POST-DECISION

Engagement, Collaboration, Data Access Rights, Information Sharing

DECISION TAKING

Automation, Modelling, Simulation, Forecasting

SENSE MAKING

Dashboards & Reporting, Real Time, Analytic, Visualisation

DATA

MANAGEMENT

DATA MANAGEMENT

Data Cleaning, Data Storage, Assets

STATE

ACADEMIA

INDUSTRY

CIVIL SOCIETY

MULTIPLE DATA r r-
SOURCES

SPATIAL a:

ECONOMIC a

ENVIRONMENTAL o

TECHNOLOGICAL c

CULTURAL r

SOCIAL a

TYPES OF DATA SOURCES

CCTV, Sensors, Drone Surveys, Citizens' Feedback, Satellite Imagery, GPS

DATA CAPTURING ROLES & RESPONSIBILITIES

Development of data collection tools, Contribution of data

LITERATURE REVIEW OF DICITAL TWINS | COMPARATIVE ANALYSIS OF CASE STUDIES

CASE STUDIES

After evaluating the collective practices of existing urban scale DTs, four case studies are selected by regions (Fig. 11).

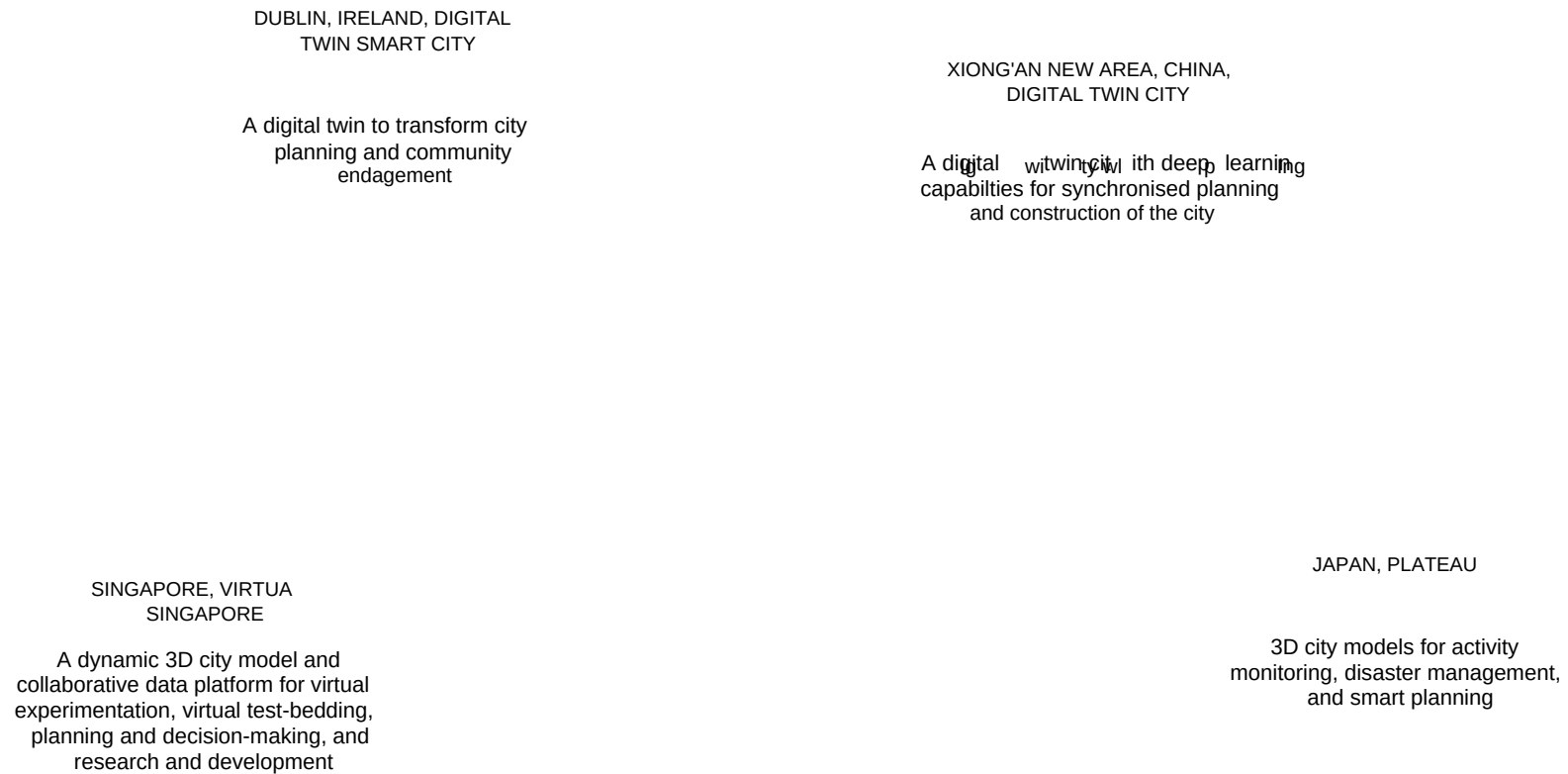


Fig. 11 Case studies of urban scale digital twins by region (Source: Authors)

LITERATURE REVIEW OF DIGITAL TWINS | COMPARATIVE ANALYSIS OF CASE STUDIES

CASE STUDIES

VIRTUAL SINGAPORE, SINGAPORE

A dynamic three-dimensional (3D) city model and collaborative data platform for virtual experimentation, virtual test-bedding, planning and decision-making, and research and development

Source: Digital Engineering Magazine (2015)

DIGITAL TWIN SMART CITY OF THE DOCKLANDS AREA, DUBLIN, IRELAND

A digital twin to transform city planning and community engagement

Source: White et al. 2021

DIGITAL TWIN CITY OF THE XIONG'AN NEW AREA, CHINA

A digital twin city with deep learning capabilities for synchronised planning and construction of the city

Source: World Economic Forum

PLATEAU, JAPAN

3D city models for activity monitoring, disaster management, and smart planning

Source: Ministry of Land, Infrastructure, Transport and Tourism

CASE STUDY 1

VIRTUAL SINGAPORE, SINGAPORE

a

8
k
s

2
s
g

2

a

i

VIRTUAL SINGAPORE

Source: GovInsider

SINGAPORE

Source: Shutterstock

CASE STUDY 1

VIRTUAL SINGAPORE, SINGAPORE

CASE OVERVIEW

“Virtual Singapore (VSg) is a collaboration between the National Research Foundation (NRF), Prime Minister's Office, Singapore, the Singapore Land Authority (SLA), the Government Technology Agency of Singapore (GovTech), and the French Dassault Systèmes (National Research Foundation, 2021; Liceras, 2019; Dassault Systèmes, France). The intention of VSg is to enhance the following four categories: 1. virtual experimentation to examine new ideas; 2. virtual test-bedding to validate provision of services; 3. planning and decision-making tool to support and develop analytical applications; and 4. research and development avenues for the research community to innovate and develop new technologies and capabilities (National Research Foundation, 2021).

SCENARIOS

VSg adopts a multi-source, multi-modal data collection approach, including data from government agencies, 3D models, information from the Internet and real-time dynamic data from Internet of Things (IoT) devices. By collecting different sources of static, dynamic, and real-time city data, e.g. demographics, movement, climate, VSg renders a number of potential uses in tackling livability issues in Singapore.

3D Modelling and Visualisation for Planning and Building Design. The semantic 3D modelling and visualisation in VSg (Fig. 12) enables the simulation of the effects of new interventions. It also provides insights into how ambient temperature and sunlight vary throughout the day in response to a particular intervention. Besides, a semi-automated planning process is made possible with an in-built filtering feature as planners efficiently filter buildings of interest according to specific parameters.

Analysis on Potential for Solar Energy Production. To enhance efforts in green energy, VSg allows the identification of suitable buildings for installation of solar panels by analysing heights of buildings, surface of the rooftops and amounts of sunlight (Fig. 13) (National Research Foundation, 2021). Potential simulation platforms, such as tree modelling with biological, spatial, and semantic representations (Gobeawan et al., 2018) and urban canopy modelling (UCM) for assessment of microclimate condition (Ilgnatius et al., 2019), have also been proposed by government-led initiatives and the research community, which have yet to be integrated into VSg.

Improved Accessibility. In terms of socio-spatial analysis, the accurate representation of the physical landscape on the platform, coupled with pedestrian movement data, allows planners to identify the most accessible and convenient routes while planning for neighbourhood inter- and intra-connectivity (National Research Foundation, 2021).

a_a
Virntua
Singapore

Fig. 12 (top) Semantic 3D modelling and visualisation in VSg; Fig. 13 (bottom) Analysis on potential for solar energy production (Source: National Research Foundation, 2021)

CASE STUDY 1

VIRTUAL SINGAPORE, SINGAPORE

CASE SUMMARY

The VSg allows its users to explore impacts of interventions as well as to develop evidence-based solutions according to the needs of the city. However, citizen participation appears yet to be fully represented in the DT. While there are intentions to show citizens upgrades to their estates (National Research Foundation, 2021), as well as a platform for citizens to voice their feedback to the relevant agencies, citizens are anticipated to be involved only at the post-decision process. Furthermore, the platform has yet to be made publicly available (Charitonidou, 2022, pp. 8-9). This implies a government-driven DT that limits the participation of the other spheres of influence, particularly at the planning phase. Furthermore, the assessment of the effects of new interventions mainly focuses on the variation of temperature and sunlight, yet has not considered the potential adverse effects on human thermal comfort. As Singapore is envisioned as a “City in Nature (National Park Board, 2022), the detailed tree modelling proposed by Gobeawan et al. (2018) renders its significance in shaping Singapore’s town planning strategies. This highlights the urgency to integrate tree modelling into the VS9g, as well as for other DTs that seek to embrace greenery as an equally important parameter to planning and building design. Despite its potential and novel uses for establishing urban planning methods, VSg has yet to represent the interdependencies and interactions between the bricks and mortar (hard) infrastructure and the social process, including social interactions, cultural practices and time-tested rituals, and economic growth. This would seem important, considering Singapore as one of the global business hubs, as well as a congenial space where different cultures coexist.

Fig. 14 The Virtual Singapore platform that transfers the entire Singapore city into virtual space as a 3D model (Source: Google Maps (top); BBC News (below))

	STATE	ACADEMIA	INDUSTRY	CIVIL SOCIETY
MULTIPLE DATA SOURCES	Aerial photography, airborne LiDAR, vehicle-mounted laser scans, geospatial and non-geospatial platforms, BIM, CIM, ICT Mobile LiDAR scanning (MLS) data, satellite imagery, airborne imagery (UPCOMING)	Airborne LiDAR scanning (ALS), mobile LiDAR scanning (MLS) data, satellite imagery, airborne imagery, IFC-BIM, Urban canopy model (UCM)	Aerial photography, airborne LiDAR, vehicle-mounted laser scans	Citizen data (demographic, movement) Citizen data (feedback) (UPCOMING)
SPATIAL	3D topographical mapping data, 2D data and information, BIM, CIM Tree data (UPCOMING)	Tree data (UPCOMING)	3D topographical mapping data	
ECONOMIC			Global industry networks (UPCOMING)	
ENVIRONMENTAL	Climate data	Urban Heat Island (UHI) data, Urban micro-climatic data (UPCOMING)		
TECHNOLOGICAL	ICT		IoT	
CULTURAL				
SOCIAL				Demographic data, movement data Feedback (UPCOMING)

CASE STUDY 2

DIGITAL TWIN OF THE DOCKLANDS AREA IN DUBLIN, IRELAND

DIGITAL TWIN SMART CITY OF THE DOCKLANDS AREA, DUBLIN, IRELAND

Source: White et al. 2021

THE DOCKLANDS AREA, DUBLIN, IRELAND

Source: Google Maps

CASE STUDY 2

DIGITAL TWIN OF THE DOCKLANDS AREA IN DUBLIN, IRELAND

CASE OVERVIEW

The 'DT smart city' of the Docklands area in Dublin, Ireland is developed as part of the 'Smart Dublin project, aiming to use 3D modelling and digital representation technology to transform city planning and community engagement (Smart Dublin, Ireland). The DT builds on six layers of information in the city (Fig. 15) (White et al., 2021):

1. Terrain — offshore boundaries, offshore boundaries, steepness of slopes or hills, water bodies, soil condition, drainage systems, sand areas, etc.;
- Building - existing buildings in the city;
- Infrastructure - infrastructure that surrounds the existing buildings in the city;
- Mobility — different transportation modes, railways and waterways network, pedestrian types;
5. Digital layer / smart city – integration of IoT sensors in the city to collect data pertinent to traffic and transport systems, utilities, power plants, crime detection, etc.; and
6. Virtual layer / DT – running of simulations based on data generated and sent from the digital layer / smart city.

SCENARIOS

The data layers in the DT have made way for different types of simulations.

Skyline Simulation. The skyline simulation allows the addition and removal of newly proposed buildings to be done easily on the DT using BIM, which is made available online for public access. This enables users, including citizens and public officials, to evaluate the impacts of new interventions on the city skyline, as well as the sunlight access of nearby parks or public spaces. With its citizen-centric approach, citizens are also allowed to vote, comment, approve or disapprove the particular interventions.

Green Space Simulation. As for green space simulation, environmental data (e.g. noise pollution, air pollution, amount of direct sunlight) and pedestrian traffic flow data are utilised to identify potential locations for green spaces in the city. Citizens are also given the platform to vote for the selection of facilities (e.g. benches, vegetation diversity) or even propose new suggestions.

5-Virtual Layer
/Digital Twin

Data simulation using smart city data

IOT integrated infrastructure
Mobile data integration
Smart vegetation sensors
Wind sensors for offshore areas

Existing modes of transportation
Vehicular Infrastructure
Pedestrian Mobility

2-Infrastructure a

Existing Physical Infrastructure
Organisational Organisational Structures

1-Buildings
i A de
dd i g

BIM data of existing built form

Offshore city extent
Existing Terrain
Existing blue infrastructure
Soil Quality
Soil drainage systems
Offshore city extent

Fig. 15 Layers required to develop a digital twin smart city for the Docklands area in Dublin, Ireland
(Source: building on White et al., 2021, pp. 2-4)

CASE STUDY 2

DIGITAL TWIN OF THE DOCKLANDS AREA IN DUBLIN, IRELAND

SCENARIOS

User-tagging & Flooding Simulation. What makes the DT unique is its user-tagging simulation, which allows citizens to tag objects and reflect real-life problems of the city by incorporating the exact geo-location as they walk around the BIM. Furthermore, in disaster mitigation scenarios, the user-tagging feature allows citizens to share their geo-location as they seek municipal assistance. Fig. 16 illustrates the interactions between citizens and the relevant authorities, industries, and research community on the online DT. The data generated over time will subsequently inform more detailed flooding simulations on the DT in regards to citizens' differential needs based on their geo-locations, coupled with actual water level and rainfall data. The simulation results, in turn, can be used to develop longer term flood prevention mechanisms by cross-analysing urban mobility and identifying flood-prone areas in the city.

Crowd Simulation. Crowd simulations are also enabled in the DT by adopting an agent-based model, allowing for more realistic reactions across different demographics to any introduced stimuli. The simulation results can then be used to derive insights into connectivity and traffic flows of the city.

CASE SUMMARY

The DT of the Docklands area inevitably deserves merit due to its people-centric approach. Despite its merit in delivering optimal people-centred services, White et al. (2021, pp. 5-6) highlight that their flooding simulation solely focuses on urban mobility and identifying flood-prone areas in the city. Hence, the capacity to forecast economic cost caused by floods has yet to be integrated into the DT, though it has been successfully implemented in other models (Pyatkova et al., 2019). Moreover, with existing software products, it is possible to extend flood simulation beyond forecasting economic cost to create flood hazard mapping for different areas, including cultural heritage sites in the city. In light of increased occurrence of heat waves, simulations of heatwave fueled forest fires will also be key to establish early warning systems of high-temperature records, as well as to inform advanced fire management and municipal preparedness and mitigation plans (Gutierrez et al., 2021; Lau and Nath, 2014).

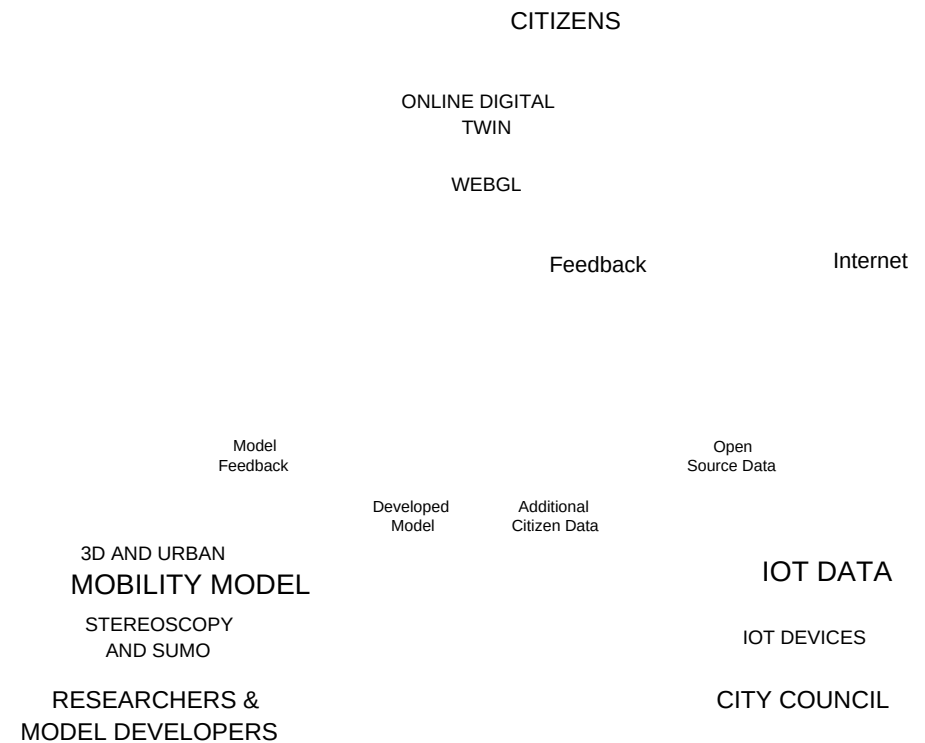


Fig. 16 Online digital twin interaction diagram. The main stakeholders for each of the components of the online digital twin are also shown with the blue box indicating the main technologies used (Source: White et al., 2021, pp. 5).

CASE STUDY 2

DIGITAL TWIN OF THE DOCKLANDS AREA IN DUBLIN, IRELAND

Open Access
Registration
Rigorous
Sharing

Proactive
Automation
Data

Urban planning and policy based on citizens' feedback
Flood planning, flood prevention mechanisms
Removing / adding of newly proposed buildings to evaluate its effect on the skyline
Developing green spaces in suitable areas based on pollution levels (air, noise), traffic flow, and amount of direct sunlight

Simulating urban mobility by different transportation modes (walking, bicycles, powered two-wheelers and generic parametrized vehicles) and pedestrian types (adult, elderly)
Modelling urban mobility based on citizens' feedback
Identifying vulnerable citizens based on geo-locations, predicting water level based on rainfall

Modelling 3D buildings based on citizens' feedback

Feedback on new urban policy and planning decisions
Access to skyline simulation to visualise the effect of new building would have on the skyline and sunlight access of its surroundings
Access to green space simulation to choose or propose new suggestions
Feedback or vote on newly proposed buildings or green spaces or propose new ideas
Access to disaster alerts

Data Boards
Reporting

Optimising traffic flow based on real-time traffic data
Improving urban IoT data based on citizens' feedback

Visualising areas and roads affected by flooding
Reporting current location and seeking assistance in disaster scenarios

DATA MANAGEMENT
Data Cleaning, Data Storage, Assets

Championing the development of DT

Developing urban mobility model

Developing of 3D building models

STATE

ACADEMIA

INDUSTRY

CIVIL SOCIETY

MULTIPLE DATA SOURCES

Aerial photography, airborne LiDAR, (moisture) sensors, CCTV cameras, anemometry, sensors (wind, seismic, people counting)

Soil survey

o BIM, stereoscopic aerial photography, 5G cell tower

Ground surveys, GPS unit, digital camera, citizen data, cellular, central monitoring system

SPATIAL

Terrain

Terrain

BIM

Infrastructure data

ECONOMIC

ENVIRONMENTAL

Vegetation moisture level, wind data, seismic data, water level / rainfall data

TECHNOLOGICAL

Public surveillance and crime-related data

City-wide internet access

Real time traffic data

CULTURAL

SOCIAL

Visitors' count to (new) green spaces

Mobility, feedback, smoke detection

CASE STUDY 3

DIGITAL TWIN CITY OF XIONG'AN NEW AREA, CHINA

DIGITAL TWIN CITY OF THE XIONG'AN NEW AREA, CHINA

Source: SOHU

XIONG'AN NEW AREA, CHINA

Source: ChinaDaily

CASE STUDY 3

DIGITAL TWIN CITY OF XIONG'AN NEW AREA, CHINA

CASE OVERVIEW

Following the announcement of becoming a Chinese national-level new area (Zou and Zhao, 2018), the Xiongan New Area (XNA) is the first area in China to create a DT city with deep learning capabilities (World Economic Forum, 2022; Hebei Xiong'an New Area Planning Outline, 2018). The objective of the DT city in XNA is to fuse the physical city and digital city through synchronised planning and construction (Zou et al., 2021), using the DT for digital supervision of urban planning, construction, management, maintenance and repair. The project is a joint research effort and collaboration amongst the government of Hebei Province, major universities, scientific research and design institutions, and construction companies in sectors such as information, construction, transportation, and finance (Chen et al., China, pp. 39-41).

SCENARIOS

The DT in XNA is designed to proceed on the basis of four platforms and five scenarios, carrying out intelligent, digital supervision in an all-around manner (Fig. 17).

Construction of Traditional Urban Infrastructure. The first platform, construction of traditional urban infrastructure, integrates city infrastructure, transportation systems, energy data, and computerisation processes to monitor public and infrastructure safety, ecological environment conservation, etc.

Construction of Infrastructure for a New Style of Intelligent [DT] City. The second platform, construction of infrastructure for a new style of intelligent [DT] city, is responsible for setting up 5G and IoT to support XNA's computing capacity (e.g. cloud, big data) and an intelligent hub.

Double Infrastructure Integration Platform. The third platform, digital city, double infrastructure integration platform, is made up of XNA's AI and DT information management centre for big data resource management systems and enhancing trust and security.

Innovation Platform. Lastly, the fourth platform, innovation platform, integrates scientific research centres, and open innovation centres to test scientific innovations and allow for business incubations.

The four platforms lay the foundation to support the DT synchronised planning and construction in the five scenarios: 7. social connectivity; 2. clean energy efficiency; 3. future mobility; 4. smart public security; and 5. scenario planning for XNA's future plans.



Fig. 17 Overview of work on Xiong'an New Area Digital Twin city (Source: Chen et al., China, pp. 41)

CASE STUDY 3

DIGITAL TWIN CITY OF XIONG'AN NEW AREA, CHINA

CASE SUMMARY

Building on the four platforms and the five scenarios, the DT city for XNA serves as an enabler for synchronised planning and construction, as well as for real-time monitoring, early warning, and condition assessments of the city (World Economic Forum, 2022). While the urban planning in XNA has been set out with five themes - environmental and ecological sustainability, spatial fairness of public service, innovation-driven economy, inheritance of history and culture, and urban governance supported by smart technologies (Zou et al., 2021) - more information is needed to understand the multi-dimensional data collected in order to achieve the five themes through the DT, especially for the representation of history and cultural heritage in the city. Besides, citizen participation is absent throughout the master plan of this DT smart city. This is not surprising since the XNA has been committed as a "top-down design and that "Beijing's administrative orders and state-owned enterprises have taken the lead in building up the New Area at its initial stage (Wong, 2019).

Fig. 18 Xiong'an BIM management platform (Source: China Academy of Urban Planning & Design)

CASE STUDY 3

DIGITAL TWIN CITY OF XIONG'AN NEW AREA, CHINA

Open Access
 Remote Access
 Data Sharing

Automation
 Data
 Storage, Assets

Synchronised planning, design, and construction
 Social connectivity
 Clean energy supply system with photovoltaic power generation
 Demand-responsive customised public transport systems and smart driving vehicles
 Enhanced response to public emergencies
 Future city scenario planning

Data Boards
 Reporting

Real-time transit information systems
 Intelligent social security prevention and control system
 Real-time environmental monitoring

Innovation & complex analysis
 Test bedding

Monitoring utilities infrastructure
 Monitoring and supervising construction of project site (people, machines, materials, methods and the environment)
 Supervising traffic and vehicles

DATA MANAGEMENT
 Data Cleaning, Data
 Storage, Assets

Championing the development of DT
 Building the Ant Financial Service Innovation Center and the blockchain infrastructure platform
 Developing intelligent industries and services

Developing and operating CIM

Constructing a full-time, global and multi-dimensional data fusion urban safety monitoring system
 Building the Ant Financial Service Innovation Center and the blockchain infrastructure platform
 Developing intelligent industries and services

STATE

ACADEMIA

INDUSTRY

CIVIL SOCIETY

MULTIPLE DATA
 SOURCES

Object-linked sensing, mobile interconnection, and AI, BIM Management Platform

CIM

Sensors, drone surveys, computing, cloud, AI, communication network infrastructure, video monitoring, access control intercom and anti-theft alarm, 5G network, Internet of Things (IoT)

SPATIAL

BIM Management Platform

CIM Platform

Utilities data, site info

ECONOMIC

ENVIRONMENTAL

Air-soil heat exchange data

TECHNOLOGICAL

Traffic & vehicle data, information technology infrastructure, big data and telecommunications data

CULTURAL

SOCIAL

Social security prevention data

*limited information is found in terms of the data layers required

CASE STUDY 4

THE PLATEAU PROJECT, JAPAN

PLATEAU, JAPAN

Source: Ministry of Land, Infrastructure, Transport and Tourism

JAPAN

Source: Google Earth

CASE STUDY 4

THE PLATEAU PROJECT, JAPAN

CASE OVERVIEW

Led by Japan's Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), the PLATEAU project is an initiative to develop 3D city models in about 50 cities across Japan. This project aims to create sustainable and human-centric urban policy, employing the 3D city models to visualise city information and generate use cases across disciplines, as well as to develop towns with citizen participation. As a collaboration between the government, research community, industries, and citizens, the knowledge and methods accumulated in the PLATEAU will be converted into open data that is accessible by everyone (Obi and Iwasaki, 2021; "PLATEAU," Japan).

SCENARIOS

The use cases in the PLATEAU are grouped into three categories: 1. activity monitoring - simulation of future city planning using movement data of people and objects (Fig. 19); 2. disaster management - strengthening regional and district's preparedness through simulations and visualisation of disaster risks (Fig. 20); and 3. smart planning - building consensus and sharing visions of urban development using smart technologies (Fig. 21).

Activity Monitoring. In view of the high population in Japan, a multi-pronged approach is adopted to understand the complexities of city's mobility, from outdoor roadside situation; indoor, underground people flow; indoor complexes human traffic; movement and retention of people in between point of interests; urban activities and human flow at shopping streets and markets; congestion status in public spaces; traffic flow; to social distancing measurement.

Disaster Management. Considering the emergence of COVID-19 and Japan's vulnerability to natural disasters, the PLATEAU has taken a holistic approach for potential use cases, integrating both top-down and bottom-up plans. This includes simulations of indoor-outdoor evacuation plans; evacuation training for citizens in cyberspace; simulation of disaster waste generation to inform preparedness, restoration, and reconstruction; disseminating disaster prevention information (e.g. evacuation facilities capacity) and raising disaster awareness; and promoting disaster prevention plans led by citizens.

Fig. 19 (left) Use cases for activity monitoring (left) and Fig. 20 (right) disaster management (right) ("PLATEAU," Japan)

CASE STUDY 4

THE PLATEAU PROJECT, JAPAN

SCENARIOS

Smart Planning. PLATEAU's smart planning is a unique interface where both top-down and bottom-up efforts meet. For top-down planning, smart planning is used for:

1. Streamlining administrative affairs and development permission procedures through City Information Model (CIM);
2. Diagnosing suitable site for developments and smart interventions based on preset city planning regulations, disaster risks, natural ventilations, Urban Heat Island, and photovoltaic power generation;
3. Visualising changes in pedestrian flow in response to new developments to improve walkability;
4. Developing sensor master plan and simulating sensor installation locations for city management;
5. Understanding actual pedestrian flow (moving route, staying time) using smart application(ICT);
Visualising effect of planning measures on urban structures; and
7. Synthesising city planning surveys overtime to prescribe land and building uses based on shifting urban and population structures.

As from bottom-up perspectives, smart planning allows anyone to create use cases and contribute to the government's database; participate in community development using the 3D city model as simulation games to interact with the layout of facilities during engagements with the agencies; receive regional information regarding events and disaster evacuation plans; and identify walking course and exercise intensity to maintain healthy lifestyles based on individual health data collected ("PLATEAU," Japan).

CASE SUMMARY

The PLATEAU positions itself as a digital platform for building resilient cities (Obi and Iwasaki, 2021), considering the holistic use cases that can be potentially generated with a middle-out approach. Additionally, elaborated and tangible methods are meticulously employed to investigate pedestrian behaviours of the cities. Despite its quantitative methods in creating extensive use cases and measuring pedestrian behaviours, the official website of the PLATEAU shows a lack of evidence in integrating the economic development and unique Japanese culture into the platform ("PLATEAU," Japan). Given Japan's influence on global economy and Japanese cultural goods and services' contributions to both local and global socio-cultureconomy (Japan Economic Foundation, 2009; Abe and Fitzgerald, 1995), it becomes essential to demonstrate the coexistence of these two layers with social, spatial, environmental, and technological elements in working together for Japan's national development.

dd
nt
d4

Fig. 21 Use cases for smart planning ("PLATEAU," Japan)

CASE STUDY 4

THE PLATEAU PROJECT, JAPAN

o pp o
Access eme o D
Rig o Sharing

Sharing of regional information platform

Sharing congestion information for crowd avoidance

Sharing congestion information for crowd avoidance
Sharing issues of the city and building consensus among various actors
Sharing of hazard maps & risk assessment
Performing disaster prevention drills with residents

Access to congestion situation
Access to improvement work status
Access to disaster prevention information, evacuation training tool
Access to upcoming development and regional activities

PP o 2
Automatio ode
atio oreca

Urban roads safety & connectivity measures
People-centric town development measures; development permissions
Disaster countermeasures & waste disposal plan
Security strategies; crime prevention measures
Regional de-carbonisation policies

Simulating people flow & measures
Simulating efficiency of security edquipment & evacuation routes
Simulating environmental factors for development site
Forecasting urban planning impacts

Building consensus for people-centric planning
Planning public health & safety measures
Modelling disaster risks and waste, evacuation behaviours & plans
Simulating efficiency of security edquipment
Modelling photovoltaic power generation

Defining voluntary disaster prevention activities of self-help and mutual assistance amongst residents

Da boards & Repo g
Re

Visualising vehicle traffic volume and speed
Visualising effects of (implemented) urban development plans
Visualising emergency-/ disaster-induced building damage
Visualising efficiency of security strategies and infrastructure

Identifying trouble spots & risks on roads
Grasping real-time people flow / congestion status
Measuring people count and retention time at public events & Pols
Understanding change in people flow before and after development/intervention; verifying the impact of large-scale development

Identifying trouble spots & risks on roads
Measuring effects of urban development plans
Monitoring movement patterns, social distancing status & facilities usage; identifying traffic obstacles
Visualising disaster risks and risk reduction improvement work; identifying potential obstacles to evacuation routes

Visualising congestion status to avoid crowd
Visualising disaster risks, identifying appropriate evacuation routes

DATA MANAGEMENT
Data Cleaning, Data
Storage, Assets

Championing the development of PLATEAU
Collaborating in the development of roadside sensing system; people flow analysis; snow damage countermeasures; security edquipment installation plan support tool; disaster waste generation simulation

Developing roadside sensing system
Developing people flow and congestion monitoring system
Developing security edquipment installation plan support tool

Developing roadside sensing system
Establishing people monitoring techniques combining multiple technologies
Developing 3D hazard maps & evacuation routes models; visualising improvement work effects
Developing security strategies support tool

Developing district disaster prevention plan

STATE

ACADEMIA

INDUSTRY

CIVIL SOCIETY

MULTIPLE DATA
SOURCES

Information models; vehicle-mounted sensors, camera images, WiFi, Census; 3D city information model

Sensors (vehicle-mounted, people flow sensors, people-counting; WiFi packet); radio waves; AI; IoT; ICT; Census; 3D WebGIS; BIM

Sensors (vehicle-mounted; people-counting); CCTV cameras; WiFi; laser sensor (3D LiDAR); Census; BIM; AI; 3D WebGIS

Citizen data (community development plan, disaster prevention plans, health data, use cases, mobility); 3D Web6GIS

SPATIAL

Road-related data; use cases; city planning information & regulations; landscape & environmental regulations

Road-related data; 3D building data; city planning information & regulations; topographical data

Road-related data; 3D building data; topographical data

Use cases

ECONOMIC

Land use status

Land use status

ENVIRONMENTAL

Hazard maps; wind data; thermal data

Historical disaster data; wind data; snow data; seismic data; disaster waste storage capacity

TECHNOLOGICAL

Telecommunications; AI; IoT; ICT; pedestrian & bicycle traffic

Telecommunications; pedestrian & bicycle traffic

CULTURAL

District disaster prevention plans; pedestrian & bicycle traffic

People flow & congestion; retention time at Pols; population density; occupancy & dereliction; evacuation facilities capacity

People flow & congestion; retention time at Pols; social distancing measures; population density; occupancy & dereliction; evacuation behaviours, action plan & facilities capacity

Mobility; demographics; health data; community development plan; disaster prevention plan

SOCIAL

SUMMARY OF COMPARATIVE ANALYSIS

CASE STUDIES ON URBAN SCALE DIGITAL TWINS

SUMMARY OF BACKGROUND STUDY AND COMPARATIVE ANALYSIS

The literature review of digital twins has sought to provide an overview of DTs, starting from the different applications of DTs to how their usage leads to varying concepts of DTs across different industries. The review of DTs in different industries has demonstrated their great potential in solving targeted issues and delivering services or products related to each field. Nevertheless, considering the urban governance and planning perspectives, the piecemeal solutions offered by potentially siloed decision-making tools have yet to solve the problems involved in the tangible and intangible complexities of the cities. This literature review reaffirms that the data-driven approach towards urban planning strategies in most DTs is "ignorant of people and what relates to them (Charitonidou, 2022, pp. 4-5).

Additionally, this work substantiates the advocacy of a quadripartite relationship between civil society, state, industry, and academia (Pomeroy, 2020b, pp. 202) since the inclusion of civil society's contributions to urban governance and planning is not prominently seen in existing DTs. It is also of utmost importance to consider both tangible hard infrastructure and intangible soft assets, encapsulated in the "six pillars", when adopting smart approaches in urban governance and planning, despite the challenge to tangibly measure the soft assets (Charitonidou, 2022; Pomeroy, 2020a; Wataya and Shaw, 2019). The abovementioned justifies the need to shift from a product-focused, to a 'people-centric' approach (Stanford Engineering, 2020) and adopt a "middle-out approach to measure both tangible and intangible assets when developing a DT for smart city urban governance and smart cities development (Centre for Digital Built Britain, 2022c, pp. 2; Stanford Engineering, 2020).

Taking stock of the four case studies selected in this work, the summary of the comparative analysis (Fig. 21) reveals that the utilisation of civil society for citizen participation and data collection is still an uncommon practice in DTs (except for the case in Dublin, Ireland and Japan). Despite the effort of most urban scale DTs in understanding social mobility, there is a lack of tangible methods for measuring other social trends, such as collective behaviours, social interactions, and social norms, which are essential to inform the functions and design of the cities. Additionally, while cities are seen to be highly influential in cultural development and the powerhouses of economic growth, it is evident that most existing DTs have yet to integrate the economic (except for the PLATEAU in Japan) and cultural elements and consider their spillover impacts on the spatial, environmental, social, and technological systems of the cities.

DIGITAL TWIN SMART CITY OF THE
DOCKLANDS AREA, DUBLIN, IRELAND

i a
DIGITAL TWIN CITY OF THE
XIONG'AN NEW AREA, CHINA

PLATEAU, JAPAN

SUMMARY OF COMPARATIVE ANALYSIS

CASE STUDIES ON URBAN SCALE DIGITAL TWINS

CASE STUDIES	VSG, S	DT OF DUBLIN, IRELAND	DT CITY OF XIONG'AN, CHINA	PLATEAU, JAPAN	VSG, SG	DT OF DUBLIN, IRELAND	DT CITY OF XIONG'AN, CHINA	PLATEAU, JAPAN	vs, S6	DT OF PBUBLN, IRELAND	DT CITY OF XIONG'AN, CHINA	PLATEAU, JAPAN	vs6, S6	DT OF PBUBLN, IRELAND	DT CITY OF XIONG'AN, CHINA	PLATEAU, JAPAN
POST-DECISION Engagement, Collab, Data Access Rights, Info Sharing																
DECISION TAKING Automation, Modelling, Simulation, Forecasting																
SENSE MAKING Dashboards & Reporting, Real Time, Analytic, Visualisation																
DATA MANAGEMENT Data Cleaning, Data Storage, Assets	4	v	v	v		v	v	v	v	v	v	v				v
		STATE				ACADEMIA				INDUSTRY				CIVIL SOCIETY		
MOL ee DATA	vv	v	v	v	v	v	v	v	v	v	v	v	vv	v		v
SPATIAL	vv	v	v	v	v	v	v	v		v	v	v		v		v
ECONOMIC								v				v				
ENVIRONMENTAL	v	v	v		v			v				v				
TECHNOLOGICAL		v						v	v	v	v	v		v		
CULTURAL																
SOCIAL		v		v				v			v	v	vv	v		v

Fig. 22 Summary of comparative analysis (Source: Authors).

V Current Features
UUUpcoming Features

PART 2: DIGITAL TRANSFORMATION IN SLOVAKIA

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

DEVISING A NEW MODEL FOR DIGITAL TWIN PARADIGM

In Alignment with Slovakia's 2030 digital transformation progress, a new model of DT paradigm for Slovakia could advocate the quadruple relationship, with greater emphasis to perceive and empower civil society as an equally important stakeholder, recognising their equitable contributions to smart city governance and planning. There is also an urgent need to develop tangible methods to quantifiably measure social trends by leveraging on predictive, algorithmic-based pedestrian modelling software (e.g. depth map), Global Positioning System (GPS) tracking devices, and social media analytic to further examine people-environment relationships and enhance the decision-making process in DTs. Lastly, more effort is required to understand how to operationalise, quantify, integrate, and represent the layers that are still absent (especially cultural and economic) in the existing urban scale DTs, as well as to create scenarios that can accurately represent the interactions between the tangible and intangible elements, just as they are in the physical world. Only by unleashing the true potential of a more inclusive, all-encompassing DT will smart cities emerge; that are fit for a dynamic population, resilient in times of crisis, and adaptable to climate change.

Whilst existing open data platforms are available across the 8 regions of Slovakia, the data **available lacks a streamlined framework for efficient interoperability**. This is a significant barrier to the implementation of a working DT, where complexity or even inability of data integration is brought about by incompatible data types and structures.

With the implementation of the new 'Spatial Planning and Construction Law', the following agenda has been set in action in the pursuit of a digitally-transformed Slovakia:

Interoperability of processes and actions

Availability of high quality, real-time data, that is reflected in the DT

Electronic services to ensure execution of E2E processes of spatial planning and building permit at Level 4 (full electronic communication on transactional level) and Level 5 (pro active, automated services) in accordance (§34 of Decree 78/2020 on standards for public administration information systems in Slovakia)

Information technology service management of the spatial planning and construction information system Urbion'



Fig. 23 8 Regions in Slovakia (Source: Authors).

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

8 REGIONS OF SLOVAKIA

BRATISLAVA

PREŠOV

Š

TRENČÍN

BANSKÁ BYSTRICA

TRNAVA

ŽILINA

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

RESEARCH METHODOLOGY

A MULTI-LAYERED APPROACH

As discussed in Part I, the digital twin aspires to go beyond the spatial, technological, and environmental pillars often found in the majority of digital twins today, by encapsulating Pomeroy's broader 6-pillars of sustainability: ie, the often-accepted social, economic, and environmental pillars that are augmented by spatial, cultural and technological pillars.

This is verified and expanded on through a 5-step process-driven approach (Fig. 24): 1) Analysis of Case Studies from Literature Review; 2) Analysis of Existing Open Data available in the Slovak Republic; 3) Data Filtering; 4) Data Categorisation; 5) Stakeholder Validation. This multi-layered process has been adopted to ensure the establishment of a broad-based, sustainable and contextual framework that is unimpeded by time or location. It further balances quantitative and qualitative data findings to offer a strategy (and eventually a proof of concept) for an effective and efficient Digital Twin in Slovakia.

Step 1: Analysis of Case Studies from Literature Review

Through academic research on existing digital twins in different regions of the world (Singapore, China, Japan, and Ireland), an initial assessment was conducted to determine the baseline data layers and indicators that are required for a digital twin. This formed the basis for a repository of potential data layers for the digital twin, which were aggregated and eventually mapped to one of the 6 corresponding pillars.

Step 2: Analysis of Existing Open Data Available in Slovakia

Beyond the literature review, a contextual investigation of available data in Slovakia was imperative to assess areas of readiness for data integration into the digital twin. Through desktop research of open data platforms in the 8 regions of Slovakia, the types of datasets and classification approaches were investigated and populated in the data layer repository, and similarly aggregated and categorised into one of the 6 corresponding pillars.

Step 3: Data Extraction & Filtering

With Steps 1 and 2 providing a two-layered approach for amassing a data layer repository for the digital twin, Step 3 sought to extract critical data relevant to the DT and its uses. Once the data layers were extracted from analyses done in Steps 1 and 2, a filtering process was done to screen those that are relevant in the context of the built environment. This process of curation and selection provided greater clarity to the digital twin and will become richer in time, as more data is collected and filtered.

Step 4: Data Categorisation

Having established a repository of data layers from both the literature review of existing digital twins and existing open data in Slovakia, it was observed that the data classification approach varies across different digital twins as well as across the 8 regions in Slovakia. This necessitated a common framework to unify existing data to pave the way for interoperability and collaboration across different regions in Slovakia, with stakeholders from state, industry, academia, and civil society. Pomeroy's broad six-pillar framework: (social, economic, environmental, spatial, cultural and technological) is used as a common data classification structure, which can potentially streamline and standardise the digitisation process across Slovakia, enabling progress as a sustainable smart nation through its digital transformation.

Step 5: Stakeholder Validation

The intuitiveness of the data layer categorisation is further tested and validated through engagement with the 4 stakeholder spheres: state, industry, academia and civil society. Through the qualitative research method: "card sorting", that is employed to understand how people organise and categorise information and their choices (Brent et al., 2021), all 4 stakeholder groups were engaged to gather a broad range of feedback. This sought to refine the digital twin data layer and indicator categorisation within the 6 pillars, culminating in a more inclusive and user-centric digital twin strategy for Slovakia.

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

RESEARCH METHODOLOGY

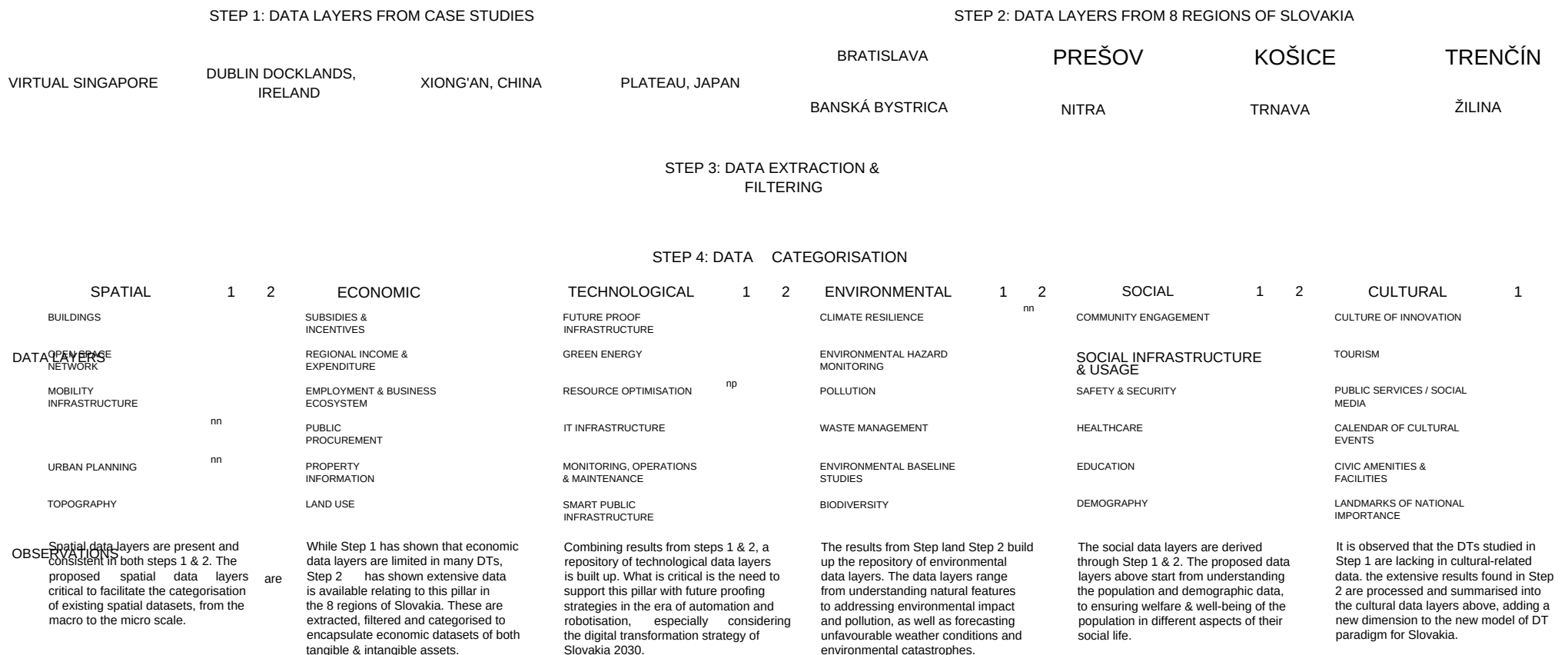


Fig. 24 Research Methodology framework (Source: Authors).

STEP 3: DATA EXTRACTION & FILTERING

STATE, INDUSTRY,
ACADEMIA, CIVIL SOCIETY

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

PURPOSE-LED DIGITAL TWIN WITH 6 PILL

PILLAR 1: SPATIAL

A geospatial visualisation tool for citizens; a planning, development and construction tool for statutory submissions, academic research and corporations.

PILLAR 2: ECONOMIC

A quantity surveying tool to gauge development and operational costs; a predictive tool to forecast gross development and real estate value for strategic investment.

PILLAR 3: TECHNOLOGICAL

A sensing tool to monitor consumption patterns; optimise and manage maintenance and operations of city infrastructure without any technical downtime.

Spatial elements are represented in this pillar to highlight the existing physical environment.

Economic data relating to landuse, property, spending patterns and employment data, is visualised in this pillar.

Information Technology and energy infrastructure are highlighted in this pillar to facilitate city operations.

DIGITAL TRANSFORMATION IN SLOVAKIA | DIGITAL TWIN FRAMEWORK FOR SLOVAKIA

PURPOSE-LED DIGITAL TWIN WITH 6 PILLARS

PILLAR 4: ENVIRONMENTAL

An early warning system and risk management tool to future proof the city through collaboration with state agencies, organisations, academia, and citizens.

PILLAR 5: SOCIAL

A visualisation of socio-demographic shifts and changing social patterns to cultivate citizen participation and identify social gaps and bias to enhance quality of life.

PILLAR 6: CULTURAL

A platform to cultivate community appreciation of cultural heritage through the retracing of historical sites and mining of local stories from crowdsourced data.

Dynamic environmental data is simulated and visualised to forecast and implement preventive measures.

Social and pedestrian data is collected, visualised and simulated to integrate citizen behaviour into future planning.

Key heritage sites and cultural events are visualised in this pillar to cultivate citizen appreciation of arts and culture.

a

SPATIAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

Spatial elements are represented in this pillar to highlight the existing physical environment, from topography, planning boundaries, utilities, mobility and green infrastructure, to buildings. This will allow the user to get a full picture of the baseline conditions to plan for future developments, identify routes, and ultimately get a sense of the “static physical and tangible elements that are represented in the virtual world.

- V

o oc

Plains, mountains and water
bodies in the region

URBAN PLANNING

District and municipal
boundaries

Water and wastewater
infrastructure

MOBILITY INFRASTRUCTURE

Roads and public
transport network

OPEN SPACE NETWORK

Tree inventory and
green spaces

pc

Buildings planned, under
construction and conserved

SPATIAL

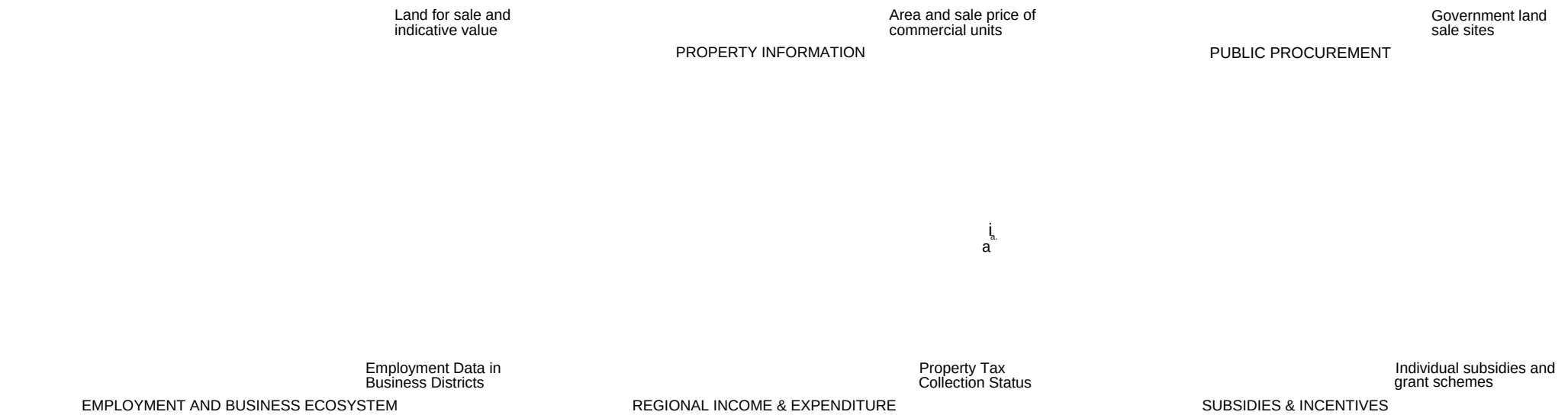
DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS	INDICATORS
URBAN PLANNING	Existing
	Derelict
	Under construction
	Planned/Proposed
	Heritage/ Conservation
OPEN SPACE NETWORK	Parks and nature reserve
	Undeveloped open space
	Tree inventory
	Landscape replacement area
	Pedestrian Infrastructure
MOBILITY INFRASTRUCTURE	Existing and proposed roads
	Public transport network
	Locations of mass transit stops
	Parking Infrastructure
	Micromobility Infrastructure
UTILITIES	Water infrastructure
	Wastewater infrastructure
	District heating network
	Electricity network
	Natural gas supply network
URBAN PLANNING	Regional/District/Municipal boundaries
	Urban/Rural boundaries
	Landuse plans
	Zoning plans
	Urban design guidelines
ENVIRONMENTAL DATA	Soil type
	Contours and elevation data
	Water bodies
	Mineral resources and mines

ECONOMIC

DATA LAYERS | CATEGORISATION OF DATA LAYERS

It is observed in Part I, that the economic pillar is one that is seen to be minimally substantiated in other DTs as compared to the other pillars. The DT will be enriched with economic data relating to landuse, property, spending patterns and employment data, to allow users to make informed decisions for strategic investment. Socio-economic information can also be gleaned from the data layers in this pillar, enabling inclusive city planning.



ECONOMIC

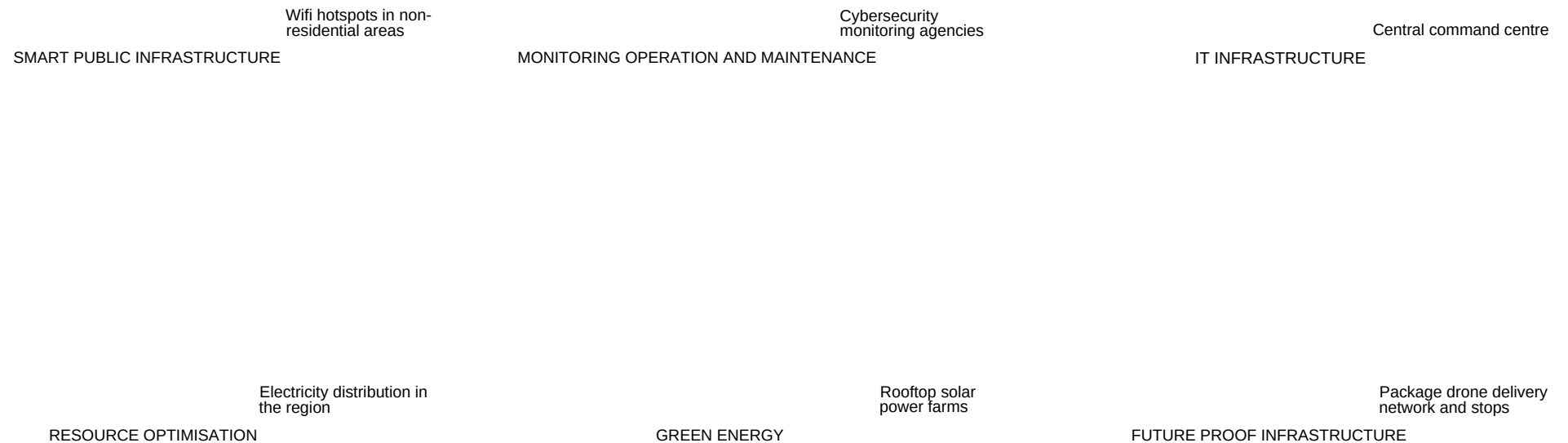
DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS	INDICATORS
SUBSIDIES & INCENTIVES	- Subsidies for individuals - Subsidies for business - Grant schemes for promoting intangible cultural heritage and cultural awareness activities - Incentives for digital transformation - Incentives for sustainable development
REGIONAL INCOME & EXPENDITURE	- GDP nominal and PPP - Revenue generated per sector - Property tax collections and status - Direct/Indirect tax collections - Spending pattern per sector
EMPLOYMENT & BUSINESS ECOSYSTEM	- Employment data - Centralised available jobs repository - Registered businesses and associated data - Revenue generated per sector - Gig business and employment monitoring
PUBLIC PROCUREMENT	- Construction service tenders - Goods and services tenders - Government registered suppliers - Public sector panel of consultants
PROPERTY INFORMATION	- Commercial property for rent/sale - Residential property for rent/sale - Industrial property for rent/sale - Transaction values over a period of 5 years - Property taxes & stamp duty - Gross development value
LANDUSE	- Permitted uses - Land ownership record - Land for sale public/private - Development permit status and conditions

TECHNOLOGICAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

The technological pillar is critical to the facilitation of city-wide operations, maintenance and optimisation. This involves the mapping of public infrastructure, including real-time data such as public transport and telecommunications information. This is further enhanced by monitoring facilities such as a Central Command Centre, as well as resource optimisation technologies to future-proof the city and rollout resilient infrastructure.



TECHNOLOGICAL

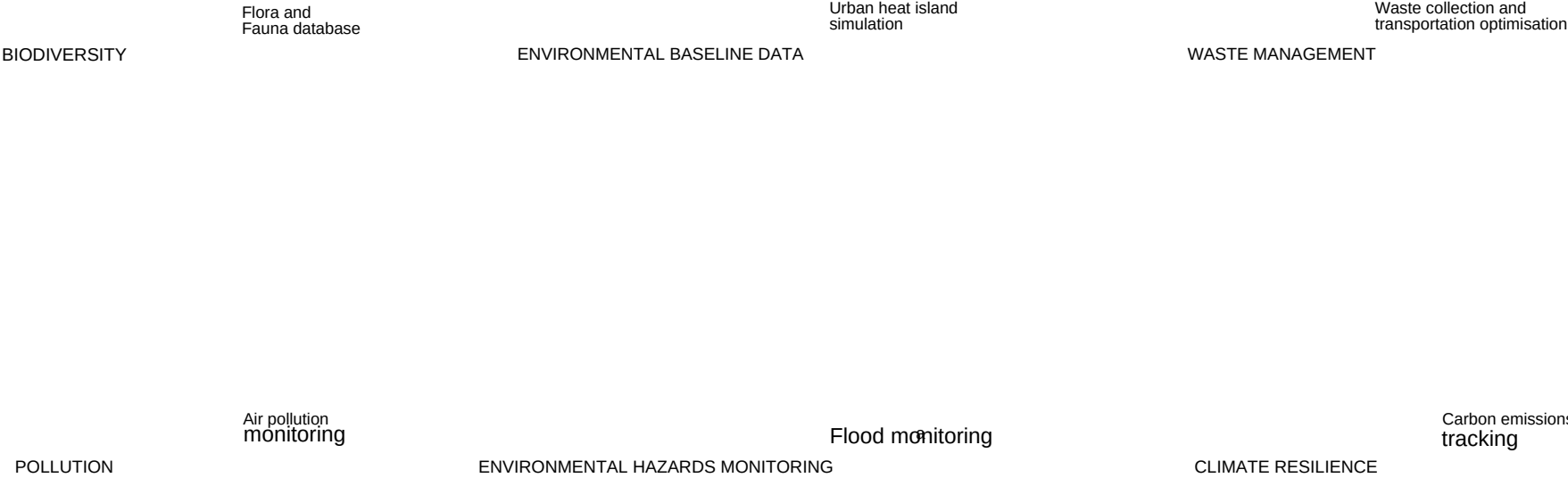
DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS	INDICATORS
FUTURE PROOF INFRASTRUCTURE	Autonomous vehicle ready infrastructure Air Mobility & delivery Water Mobility Blockchain technology deployment
GREEN ENERGY	Existing/Proposed alternate energy sources infrastructure Energy split, pricing and utilisation Off-grid energy production National battery storage network
RESOURCE OPTIMISATION	Household/industrial water consumption Household/industrial Electricity consumption Irrigation water use for agriculture Mining and dquarrying extraction / exploration
IT INFRASTRUCTURE	Data/cloud storage network and capacity Central command centre Internet distribution network and usage
MONITORING, OPERATIONS AND MAINTENANCE	Gas/Water leakage detection and control Water duality monitoring Public Infrastructure maintenance schedules Solid waste management Cybersecurity Monitoring
SMART PUBLIC INFRASTRUCTURE	Sensor network WiFi hotspots Live Traffic Information Live Public Transport Information CCTV Surveillance network

ENVIRONMENTAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

Dynamic environmental information is simulated and visualised on the DT to allow for climate-responsive planning interventions. This will support environmental hazard monitoring and serve as an early warning system for citizens in vulnerable regions. Through monitoring of environmental conditions, pollution levels and waste, riskmanagement measures can be strategically implemented to transform the city into one that is more resilient, healthier and safer for its inhabitants.



ENVIRONMENTAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS

INDICATORS

CLIMATE RESILIENCE

Carbon credits tracking
Circular economy monitoring
Biodiversity index
Decarbonisation tracking

ENVIRONMENTAL HAZARD
MONITORING

Landslides
Forest Fires
Earthquake Monitoring
Flood Monitoring
Radiation and Biohazard

POLLUTION

Air pollution
Water pollution
Noise pollution
Soil contamination

WASTE MANAGEMENT

Collection data
Segregation data
Transportation optimisation
Processing and recycling
Dumping/landfill data

ENVIRONMENTAL BASELINE
STUDIES

Meteorological
Sunpath and shadow data
Ambient air quality
Noise data
Water duality
Land environment
Ambient temperature

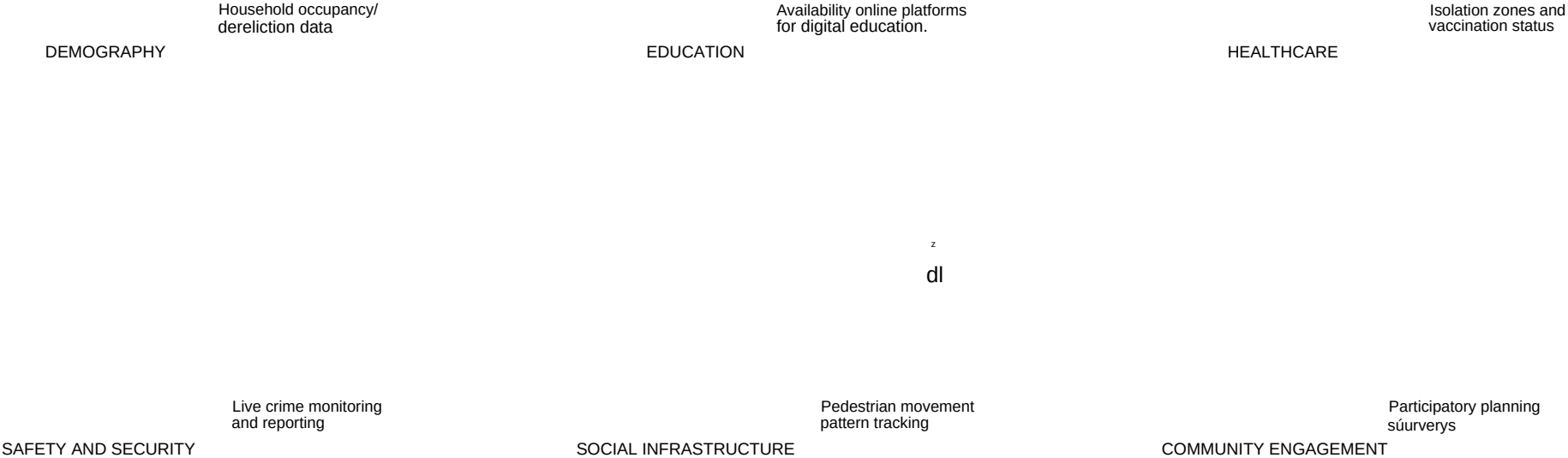
BIODIVERSITY

Plant data
Animal data
Ecosystem data
Genetic data

SOCIAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

The social pillar collects and visualises demographic data, education, healthcare, social infrastructure, and utilisation patterns by citizens. Gauging public acceptance and frequency of use of services and infrastructure will enhance efficiency and advocate a citizen-centric approach to planning of a safer, more sustainable, inclusive and equitable nation. Social gaps and bias can also be identified to allow for targeted aid to enhance standard of living and quality of life of citizens.



SOCIAL

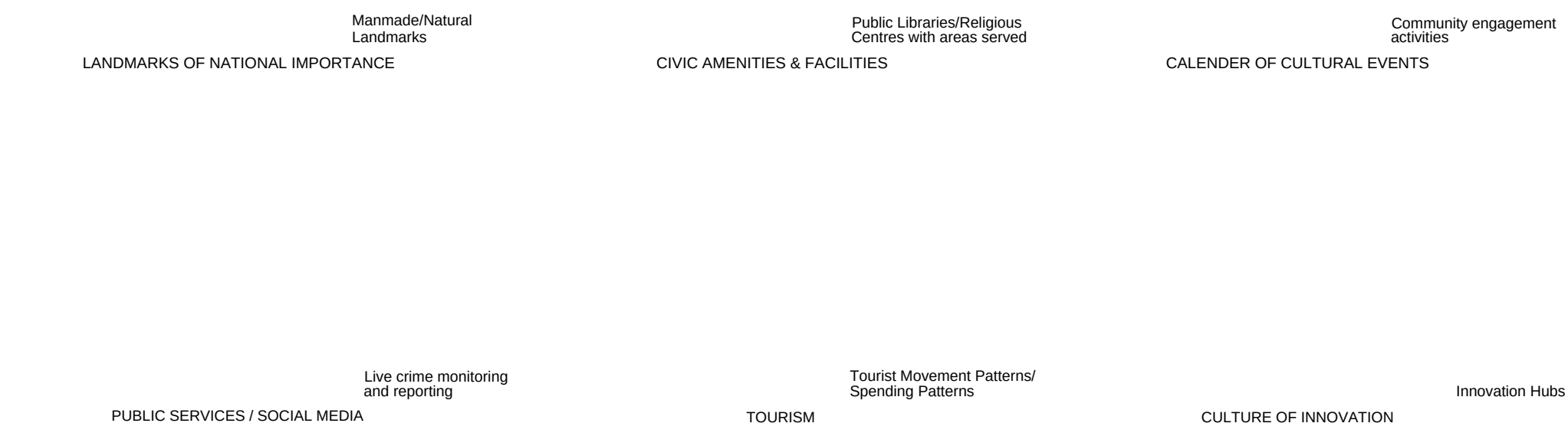
DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS	INDICATORS
COMMUNITY ENGAGEMENT	Participatory Planning Community Resilience tracking Community action plans
SOCIAL INFRASTRUCTURE	Pedestrian movement patterns tracking Accessible facilities and amenities Seniors tracking and monitoring Social services Volunteer services
SAFETY AND SECURITY	Live Incident/crime monitoring Crime prevention by design Citizen on patrol Substance abuse monitoring Emergency response and planning
HEALTHCARE	Digital health services Public health warnings clusters and quarantine zones Vaccination coverage Healthy living initiatives
EDUCATION	Digital literacy Online education Life long learning UÚUpskilling initiatives
DEMOGRAPHY	Population Household and Housing Family Formulation and dissolution Fertility and Mortality Employment Education

CULTURAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

Cultural nodes and points of interests such as heritage monuments and historicalsites are highlighted in this pillar, alongside time-based practices such as pop-up events or exhibitions. Local events and stories are also populated in the DT, cultivating citizen appreciation and engagement with arts and heritage, through crowdsourced data. The DT also seeks to spur a culture of innovation through the mapping of creative spaces such as fablabs and events such as hackathons.



CULTURAL

DATA LAYERS | CATEGORISATION OF DATA LAYERS

DATA LAYERS	INDICATORS
CULTURE OF INNOVATION	Hackathons Startup Incubators. Innovation hubs Fablabs
TOURISM	Number of tourists Tourist Movement Patterns Tourist Spending Pattern
PUBLIC SERVICES / SOCIAL MEDIA	One stop shop Municipal maintenance tracking Social media data aggregation Live event tracking
CALENDER OF CULTURAL EVENTS	Festivals / Carnivals Public Awareness Campaigns Calendar of events Community Engagement Activities
CIVIC AMENITIES & FACILITIES	Public libraries Museums, galleries & performance venue Civic engagement centres Religious centres & churches
LANDMARKS OF NATIONAL IMPORTANCE	Natural Landmarks of cultural importance Man-made Landmarks of cultural importance

DATA LAYERS | A PURPOSE-LED DIGITAL TWIN WITH 4 SPHERES OF INFLUENCE

4 SPHERES OF INFLUENCE IN SLOVAKIA

As discussed in Part I, strategic partnerships are critical to creating a successful and sustainable product. Pomeroy's four spheres of influence: state, industry, academia and civil society, are key to urban governance and development in the long-run. Through the process of analysing existing open data in the 8 regions of Slovakia, it became apparent that there are central bodies of state administration that form the consistent data contributors at the national level, namely the Statistical Office of the Slovak Republic. Such central bodies are supported by other government agencies (state), corporate stakeholders (industry), universities and research labs (academia), and citizens (civil society).

Having a collaborative framework ensures that the DT is attuned to the needs of citizens, features up-to-date technologies that begin in the realm of academia and industry, and is regulated and protected by state bodies to mitigate risks such as cybersecurity threats and data protection vulnerabilities. Such partnerships will also allow for more sustained systemic change, where citizens are able to provide feedback and input through the DT that can be screened and conveyed to relevant policy-makers. The DT provides an open channel of communication that is typically closed and limited by bureaucratic red tape.

Fig. 25 illustrates key potential stakeholders from each of the four spheres, for strategic partnership in the development of the DT in Slovakia.

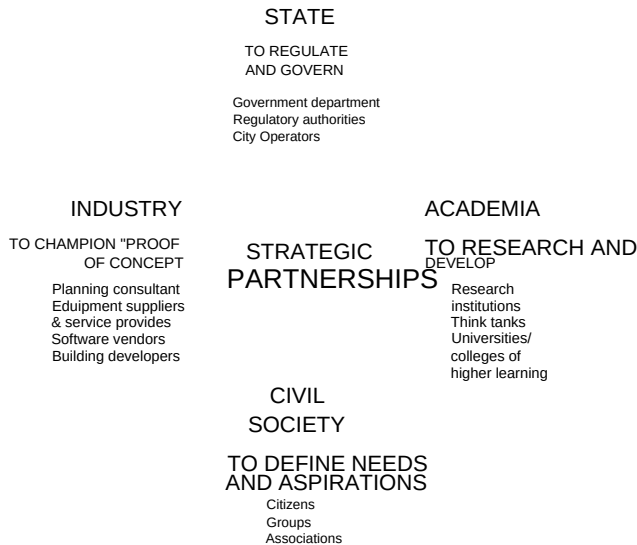


Fig. 25 Stakeholders in Slovakia (Source: Authors).

ACADEMIA

INDUSTRY

CIVIL SOCIETY

SOCIAL ENVIRO TECH ECON SPATIAL

BUREAU FOR SPATIAL PLANNING & CONSTRUCTION
MINISTRY OF TRANSPORT & CONSTRUCTION
MAGISTRATE OF THE CAPITAL CITY OF THE SR
SLOVAK ROAD ADMINISTRATION
GEODESY, CARTOGRAPHY AND CADASTRE AUTHORITY

MINISTRY OF ECONOMY
MINISTRY OF FINANCE

STATISTICAL OFFICE
MINISTRY OF REGIONAL DEVELOPMENT
& INFORMATISATION
INNOVATIONS OF BRATISLAVA (INOVÁCIE
MESTA BRATISLAVA)

MINISTRY OF ENVIRONMENT
MINISTRY OF AGRICULTURE
SLOVAK GREEN BUILDING COUNCIL
INSTITUTE FOR ENVIRONMENTAL POLICY (IEP)
SLOVAK ENVIRONMENT AGENCY
SLOVAK HYDRO-METEOROLOGICAL INSTITUTE

MINISTRY OF EDUCATION, SCIENCE, RESEARCH & SPORT
IMPLEMENTATION UNIT (IMPLEMENTAČNÁ
JEDNOTKA, IJ)
OFFICE OF LABOUR, SOCIAL AFFAIRS & FAMILY
MINISTRY OF INTERIOR
SLOVAK CHAMBER OF SOCIAL WORKERS &
SOCIAL WORK
PUBLIC HEALTH AUTHORITY

MINISTRY OF CULTURE
SLOVAK ARTS COUNCIL
SLOVAK CONVENTION BUREAU
MUNICIPAL ADMINISTRATION OF MONUMENT CARE AND
NATURE CONSERVATION OFFICE

SOCIAL ENVIRO TECH ECON SPATIAL

ARCHITECTURE & DESIGN (FAD), STU
FACULTY OF GEOGRAPHY, COMENIUS UNIVERSITY

UNIVERSITY OF ECONOMICS, BRATISLAVA
SOCIAL & ECONOMIC SCIENCES, COMENIUS UNIVERSITY

INFORMATICS & TECHNOLOGY, STU
ELECTRICAL ENGINEERING AND INFORMATION
TECHNOLOGY, STU
TECHNICAL UNIVERSITY OF KOŠICE
SLOVAK ACADEMY OF SCIENCE

ENVIRONMENTAL ENGINEERING, STU
NATURAL SCIENCES, ENVIRONMENTAL STUDIES,
COMENIUS UNIVERSITY

BRATISLAVA POLICY INSTITUTE

CENTRE FOR RESEARCH OF ETHNICITY & CULTURE
(CVEK)

SOCIAL ENVIRO TECH ECON SPATIAL

PUBLIC TRANSPORT COMPANY SLOVAKIA (SR
RAILWAYS, SR LINES)
REAL ESTATE DEVELOPERS SLOVAKIA
ENERGY & GAS COMPANIES
WATER INDUSTRIES

KPMG SLOVAKIA
NATIONAL BANK OF SLOVAKIA (NBS)
SLOVENSKÁ SPORITELŇA

ESRI
GREEHILL
EMERSON
SOVA GROUP
TELECOMMUNICATION ORGANISATIONS

ENVIRONMENTAL INSTITUTE (EI)
WASTE MANAGEMENT 8 RECYCLING COMPANIES
SLOVAKIA
ENVI

SOCIAL ENTERPRISES SLOVAKIA

SLOVAK TOURIST BOARD

SOCIAL ENVIRO TECH ECON SPATIAL

METROPOLITAN INSTITUTE OF BRATISLAVA
OPEN STREET MAP

ORGANISATION FOR ECONOMIC CO-OP &
DEVELOPMENT (OECD)

ASSOCIATION OF SLOVAK SCIENTIFIC & TECH SOCIETIES
(ZSVTS)
GLOBSEC

GREENPEACE SLOVENSKO
INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS
ANALYSIS (IIASA)

CREATIVE INDUSTRIES KOŠICE
AKO
"MESSAGE FOR THE MAYOR" TEAM
GREEN FOUNDATION

ETHNOGRAPHIC SOCIETY SLOVAKIA

PART 3: ENABLING THE DIGITAL TWIN IN SLOVAKIA

INFORMATION
MANAGEMENT
FRAMEWORK; ACCESS
RIGHTS

ENABLING DIGITAL TWIN IN SLOVAKIA

A COMMON STATE / NATIONAL FRAMEWORK

Qui core nobit fugit qquatiunt lab in prat la saperibus duo blaut idic tem duid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae sitiume maion nonet ma poritet quam dquatect atintur, ommosant Corepe nusandunt quid ut a et et

FIVE LEVEL OF CHANGE

Individual Change. Qui core nobit fugit quatiunt lab in prat la saperibus qjuo blaut idic tem quid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et

Organisational Change. Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et

Sectoral Change. Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem dquid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et

National Change. Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et

International Change. Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et et

DIAGRAM: THEORY

OF CHANGE - GEMINI
PAPER (HOW)

SHORT TERM GOALS

Qui core nobit fugit quatiunt lab in prat la
saperibus quo blaut idic tem duid eum enis
reicae sitiume maion nonet ma poritet quam

STAGE 5

```
XXXXXXXXXXXXXXXXXXXXxxXxxXxxxxxx
XXXXXXXXXXXXxxXxxXxxXxxxxxx
```

LONG TERM GOALS

Qui core nobit fugit quatiunt lab in prat la
saperibus quo blaut idic tem duid eum enis
reicae sitiume maion nonet ma poritet quam

STAGE 5

XXXXXXXXXXXXXXXXXXXXXxXxXxXXXXXX
XXXXXXXXXXXXXXXXXXxXXxxXxxXXXXXX

ENABLING DIGITAL TWIN IN SLOVAKIA

SCENARIO PLANNING

Henrich, an architect from New Horizon Property, has just recently presented his vertical green design concept for a mixed use scheme to his company. Standing by the Danube River, the mixed use scheme will include a series of multi-story residential buildings, as well as commercial and civic uses on ground floor facing the river. After much deliberation, his company believes having access to a port is of added value and they anticipate premium prices for river facing residential units that come with wide balconies. Henrich and his company are in search of suitable greenfield land that will allow them to test out Henrich's design concept from the ground up. The land search criteria is set as follows:

1. It needs to be a greenfield land
2. It is a private land owned by the state that is up for sale
3. It is intended to be used mainly for mixed-use development
4. The land area must be at least 4500m², with a minimum 50m width
5. It is closer than 200m to the Danube River
6. It is closer than 200m to a port
7. It will provide a gross development value of €5,000,000

While traditional land search involves a complicated process with background study from multiple sources, the digital twin comes in handy to simplify the procedure. Henrich and his colleagues use the digital twin to manoeuvre their land search virtually, bearing in mind the criteria initiated. Switching on the various layers and inputting their criteria, the digital twin helps to narrow their options down to three land lots that fulfil the first six criteria initiated - 4500m² greenfield lands along the Danube adjacent to a port that are intended for mixed-use purpose and are up for sale.

With the three options found, Henrich makes use of the measuring tool on the digital twin to get a better glimpse of the width and length of each land lot. The best option, however, is one with a 45m lot width (instead of 50m). Knowing that he will be limited by the land size, Henrich refers to the gross plot ratio and floor area ratio designated for this particular land lot. This provides him a better understanding of the total usable space. Henrich works back and forth between BIM construction software and the digital twin, playing around with the building massing and trying out with five design iterations by pushing for greater floor area ratio (FAR) to test his vertical green design concept. Making use of the digital twin, Henrich is able to run an analysis on light intensity, reflection, and shading on the site in relation to his design iterations. This allows him to strategically locate his vertical green walls and facades. Lastly, Henrich imports his design iterations as a BIM to the digital twin and runs a property value analysis, a built-in analytical tool, for all the iterations, among which Henrich picks the one with a forecasted gross development value of €5,003,650, this makes the last criteria met. In light of the Construction Act and Spatial Planning Act, where the entire process of construction permitting is shifted to be conducted electronically in the Urbion information system, hosted on the digital twin platform, Henrich and his colleagues proceed to make a digital submission for their construction plan.

ECON To run property value analysis by incorporating spatial components and location analytics, market databases, and historical returns, past transaction values, surrounding property values, etc.
To understand valuation with spatial components and how the design iterations fit into the particular district / neighbourhood.

ENVIRON ENVIRONMENTAL BASELINE STUDIES

To study the environmental conditions of the land lot, e.g. seasonal and diurnal sun path, seasonal and diurnal shadow, surface albedo

To obtain information on plot ratio and floor area ratio (FAR) designated for the land lot

ROAD NETWORKS, PATHWAYS, ROUTES

To identify land lots (stipulated based on step 1-3) that are within 200m buffer of ports locations

To identify land lots (stipulated based on step 1-2) that are within 200m buffer along the Danube River

To identify land for sale and areas intended to be used mainly for mixed-use development. The land area needs to be at least 4500m²

SPATIAL PLANNING

To identify greenfield lands for development

d 6

GREEN IFR ASTAUCTt RE

ENABLING DIGITAL TWIN IN SLOVAKIA

SCENARIO PLANNING

Lukas, an officer from the Office for Spatial Planning and Construction of the Slovak Republic, receives the construction plan submitted by Henrich's company through the information system on the digital twin. He publishes Henrich's proposed construction plan, making it available to all relevant parties to share their comments and generate a discussion of the construction plan submitted. The relevant parties include state administration bodies, affected legal entities, the municipality in whose territory the development is to be built, and the owners of neighbouring buildings and land.

Jakub owns a building adjacent to the land lot where Henrich's mixed use scheme will be potentially built upon. As soon as Henrich's construction plan is made known on the digital twin, Jakub's worries mount about his roof-mounted solar panels. Using the built-in analytical tools on the digital twin, Jakub runs a shadow analysis to understand the shadow-cast effect by Henrich's mixed-use scheme and realises part of his solar panels will remain in a shadow all year round. Jakub follows up his assessment on the digital twin by running a solar energy production analysis based on the the results obtained from the shadow analysis - it is discovered that the solar energy produced for his building will reduce by 20%. Without further ado, Jakub sends his comments to the system on the digital twin to express his concerns about Henrich's mixed-use scheme, supported by the quantitative results generated from the analyses.

Barbara, an officer from the Ministry of Environment, refers to the Environmental Impact Assessment (EIA) done for Henrich's construction plan. The EIA highlights concerns about the vertical green walls and facade proposed in Henrich's mixed-use scheme, specifically due to its high building density (optimised plot ratio and FAR). Barbara uses the digital twin to perform additional environmental baseline analysis. She finds out the greater wind speed and the higher temperature at the upper levels will lead to an increased risk of plant dehydration at those levels of the proposed building design. Barbara carries on with further analysis to study the interaction between air pollutants in that area and the pollen grains that will potentially come from Henrich's proposed green design. Through the digital twin, she shares the analysis results and specifically advises on the plant selection to prevent any potential risk of plant dehydration and pollen allergenicity.

The tangible analysis results and comments shared on the digital twin allows Henrich to effectively geo-visualise the impacts of his proposed mixed-use scheme on the surrounding environments and local population in the vicinity. He revises his design accordingly and runs different analyses on the digital twin to evaluate his revised mixed-use scheme, not only to make sure similar mistakes are not repeated but also to help him optimise the potential of his vertical urban green design to become an integrated part of the ecosystem in the area, contributing to greater social and environmental benefits. As Henrich has previously submitted his construction plan, the resubmission for his revised construction is made friendly and convenient since the system already has some information stored on the cloud. While Lukas sees certain benefits that Henrich has suggested in his revised construction plan, he wants to be more cautious about flood management and the impact of Henrich's vertical urban green design especially when constructing a high-rise, high-density building by the Danube River.

ENVIRON

POLLUTION

To study the interaction between air pollutants and pollen grains coming from the urban greenery

ENVIRONMENTAL BASELINE STUDIES

To examine the seasonal and diurnal wind speed and direction
To study the seasonal and diurnal temperature, precipitation, rainfall, and relative humidity

IT INFRASTRUCTURE & ENERGY TECH

To run analysis on solar energy production

ENVIRON

ENVIRONMENTAL BASELINE STUDIES

To run shadow analysis and examine the shadow-cast effect by Henrich's construction plan

MOBILITY FRA TS

LC

a

ENABLING DIGITAL TWIN IN SLOVAKIA

SCENARIO PLANNING

Laura runs an interdisciplinary research lab, Human(e) Lab, that investigates human-environment relationships. Laura has been appointed by Lukas to run a more in-depth study on Henrich's design ideas in relation to the geographical location and socio-environmental aspects of the site. Henrich's design ideas include landscaping the boardwalk on the ground floor facing the Danube and having vertical urban greenery on the balconies of the multi-story residential units. Literature review suggests that many successful new approaches are based on a mix of blue and green solutions by creating a "safe-to-flood" landscaping zone to enable flood adaptation. Further academic research also shows positive results for soakaways in flood mitigation. To validate Henrich's design ideas, Laura needs to:

Run a flood simulation to evaluate impacts of the recurring Danube flood on the proposed design

Conduct pedestrian modelling to examine the boardwalk landscape location for social benefits

Perform microclimate modelling to investigate the impact of the vertical urban greenery on thermal comfort and the environment

Laura uses the digital twin to extract all the information pertinent to Henrich's revised construction plan and runs a flood simulation. The simulation results show that the boardwalk landscape design is effective to reduce flood vulnerability and at the same time provide a range of ecosystem services to the local populations in the vicinity. Pedestrian modelling also ensures the boardwalk landscape is located in the appropriate spot, as it has high accessibility to activities in the surrounding amenities. Lastly, Laura runs a microclimate model to study the effects of the vertical urban greenery proposed by Henrich. The results show that the "green curtains" on the balconies do not only help to regulate humidity, but also filter (instead of reflect or magnify) the sun's rays, hence, creating a welcoming internal microclimate without posing harmful effects on the environment. Considering the drier season in Bratislava, which averagely lasts for about seven months a year, Laura advises on the technical specifications for integrating a smart irrigation system into Henrich's building design.

Henrich, Lukas, and Laura establish a common understanding that there is a value in the proposed mixed-use scheme but yet there is also a need to create a proof of concept by testing out the design in a sandbox environment. In order to move forward, more rigorous tests will be redquired and documented, made friendly through the digital twin, to help shape the legislation for onward civil society benefits.

ENVIRON

ENVIRONMENTAL BASELINE STUDIES

To run microclimate model and study the effects of the vertical urban greenery

§

ROADS NETWORKS,
PATHWAYS, ROUTES

. To identify land lots (stipulated based on step 1-3) that are within 200m buffer of ports locations

4...

a
o
9

SOCIAL INFRASTRUC-

ENVIRONMENTAL
HAZARD MONITORING

292...

ENVIRONMENTAL
BASELINE STUDIES

To run flood simulation and evaluate impacts of recurring flood on the proposed design, based on topography and environmental baseline of the land lot, as well as the historical data from flash od on Itol ino

SPATIAL

TOPOGRAPHY

GREEN IFR ASTAUCTt RE

MBL INFRA TR T TUR

TOP OGRAPHY

ENABLING DIGITAL TWIN IN SLOVAKIA

SCENARIO PLANNING

Mikolás and Xénia, a young couple who love art and culture with a baby on the way, are planning to upsize to a bigger home as they anticipate a fresh start with a forthcoming new addition to the family. Growing up in the city, both of them are emotionally attached to the Danube River. Their ideal home is one that comes with a river facing view and a large balcony, where they can spend their evenings sitting on the balcony, enjoying sunsets by the river. Hence, their apartment hunting criteria includes:

1. It must be closer than 200m to the Danube River
2. It is a three-bedroom, high floor, river facing unit with a large balcony
3. It has a minimum size of 200m², at a cost of less than €600,000.00
4. It must be within reasonable driving distance of a childcare service (say 1km)
5. It is accessible to museums and art galleries (say 1km)

With a digital twin that is made publicly available, Mikolás and Xénia are able to learn about Henrich's mixed-use scheme, though it is still pending construction permit. Not only does the digital twin provide transparency to the state of play in the construction permitting process, it also publishes the milestones and achievements of Laura's ongoing research, which is deemed to offer greater environmental protection. Excited by Henrich's mixed-use scheme, Mikolás and Xénia use the digital twin to further examine whether they can find any particular residential unit that meets the criteria initiated. The digital twin gives them the flexibility and convenience to filter out those units that are irrelevant to their interests, and they finally end up with three units that meet most, if not all, of the criteria set. As soon as the construction permit is granted and the development is open for sale, Mikolás and Xénia proceed to purchase their ideal home.

Throughout the construction process, Henrich's company uses the digital twin to engage all prospective residents, giving Mikolás and Xénia the chances to contribute to the eventual appearance of their ideal home (e.g. colour scheme, gym equipment, retailers, etc.). The entire construction process takes two full years, and they move into their ideal home as soon as they receive their key.

A few months after moving in, Mikolás and Xénia's friends and family from Budapest decide to pay them a visit as they organise a housewarming party. Without any prior knowledge of the area, their friends and family use the city guide app, hosted on the digital twin platform, to navigate their way to Mikolás and Xénia's apartment. What makes their trip unique is the city guide app that casts cultural landmarks in a new light, providing secret tips and quirky anecdotes that came from crowdsourcing and story mining. With the city guide app in hand, a long weekend is spent on discovering the city anew with much hiking through nature trails, cultural immersion in folklore shows and traditional Slovak dinner, and attending a classical concert.

AMENITIES & FACILITIES

To locate cultural amenities and facilities that are within 1km buffer to the property

EDUCATION

To examine whether the property falls within 1km buffer of all childcare services

PROPERTY INFORMATION

ECON

To find out the river facing, high floor, three-bedroom units with a minimum size of 200m² and a cost of less than €600,000.00

SPATIAL

TOPOGRAPHY

To identify planned buildings that are within 200m buffer along the Danube River

SPATIAL

BUILDING

To be updated on planned buildings

GR EA IM RAS TR TRE

MOEBLIT V INFRA_{kl}TR TLRE i

PAN PLA

GLOSSARY

Data Layer

Refers to a common data framework and virtual layer where data can be processed and organised accordingly, providing users with data interoperability and access to a list of indicators used to measure the respective data layer.

Digital Twin (DT)

Refers to a virtual, dynamic, three-dimensional representation of the real world - including physical objects and systems between social, economic, and digital infrastructure, as well as the natural environment.

Indicator

Refers to a list of indices used as the statistical measure to represent the different complementary aspects of the respective data layer. Each indicator can be operationalised by relevant datasets. For instance, the 'micro-mobility infrastructure' indicator can be operationalised by datasets such as micro-mobility road networks, locations of charging stations, locations of docking areas, etc.

Middle-out Approach

Refer to the combination of both bottom-up and top-down approaches.

Proof of Concepts

Refers to the pre-defined objectives in the "Urbion" programme, including: 1. the creation of a digital twin model in the selected territory of one city with the possibility of testing methodological approaches and implementation procedures; and 2) designing, implementing, testing, and evaluating the implementation through a set of sub-projects (i.e. Dendrology, Smart Zone Plan, Construction Notice, Building a House, Monitoring of Water Pipe Leaks, and Road Construction Project).

Urbion

Refers to the programme containing projects for the delivery and operation of IS (information system) spatial planning and construction (IS SPC).

GLOSSARY

BIBLIOGRAPHY

- Abe, E. and Fitzgerald, R. (1995) Japanese economic success: timing, culture, and organisational capability', *Business History*, 37(2), pp. 1-31. Available at: <https://doi.org/10.1080/00076799500000053> (Accessed: 1 August 2022).
- Agrest, D. (1980) 'The city as the place of representation', *Design Quarterly*, pp. 8-13. Available at: <https://doi.org/10.2307/4091024> (Accessed: 4 August 2022).
- Allen, B.D. (2021) "Digital Twins and Living Models at NASA", 3 November. Available at: https://ntrs.nasa.gov/api/citations/20210023699/downloads/ASME%20Digital%20Twin%20Summit%20Keynote_final.pdf (Accessed: 16 July 2022).
- Argan, G.C. and Jaffé, H.L.C. (1967) *Renaissance painting*. New York, U.S.: Dell Publishing Company.
- Batty, M. (2018) 'Digital twins', *Environment and Planning B: Urban Analytics and City Science*, 45(5), pp. 817-820. Available at: <https://doi.org/10.1177/2399808318796416> (Accessed: 4 August 2022).
- Bhavnani, S.P. and Sitapati, A.M. (2019) "Virtual care 2.0 – a vision for the future of data-driven technology-enabled healthcare", *Current Treatment Options in Cardiovascular Medicine*, 21(21). Available at: <https://doi.org/10.1007/s11936-019-0727-2> (Accessed: 18 July 2022).
- Booth, C. (1889) 'Descriptive map of London poverty'. London, UK: British Library. Available at: <https://www.bl.uk/collection-items/charles-booths-london-poverty-map> (Accessed: 26 July 2022).
- Bruynseels, K., Filippo, S.D.S. and Jeroen, V.D.H.. (2018) 'Digital twins in health care: ethical implications of an emerging engineering paradigm', *Frontiers in Genetics*, 9. Available at: <https://doi.org/10.3389/fgene.2018.00031> (Accessed: 18 July 2022).
- Centre for Digital Built Britain (2021) *The value of Information Management in the construction and infrastructure sector*. Cambridge, United Kingdom: Centre for Digital Built Britain. Available at: https://www.cdbb.cam.ac.uk/files/cdbb_econ_value_of_im_report.pdf (Accessed: 22 July 2022).
- Centre for Digital Built Britain (2022a) *Gemini papers: what are connected digital twins*. Cambridge, United Kingdom: Centre for Digital Built Britain. Available at: <https://doi.org/10.17863/CAM.82194> (Accessed: 29 June 2022).
- Centre for Digital Built Britain (2022b) *Gemini papers: why connected digital twins*. Cambridge, United Kingdom: Centre for Digital Built Britain. Available at: <https://doi.org/10.17863/CAM.82237> (Accessed: 10 July 2022).
- Centre for Digital Built Britain (2022c) *Gemini papers: how to enable an ecosystem of connected digital twins*. Cambridge, United Kingdom: Centre for Digital Built Britain. Available at: <https://doi.org/10.17863/CAM.82193> (Accessed: 12 July 2022).
- Charitonidou, M. (2022) "Urban scale digital twins in data-driven society: challenging digital universalism in urban planning decision-making", *International Journal of Architectural Computing*. Available at: <https://doi.org/10.1177/14780771211070005> (Accessed: 28 June 2022).
- Chen, Y., Lai, N. and Zhang, X. (n.d.) *China's city of the future: Xiong'an New Area*. Global Innovation Report, pp. 36-44. Available at: https://www.hitachi.com/rev/archive/2021/r2021_01/pdf/gir.pdf (Accessed: 26 July 2022).
- Coates, P. et al. (2010) "The changing perception in the artefacts used in the design practice through BIM adoption", in *CIB 2010 World Congress Proceedings*. University of Salford, United Kingdom, pp. 1037-1048. Available at: <http://eprints.hud.ac.uk/id/eprint/25938> (Accessed: 26 July 2022).
- Dassault Systèmes (no date) *Virtual Singapore*. Available at: <https://www.3ds.com/insights/customer-stories/virtual-singapore> (Accessed: 25 July 2022).
- Deng, T., Zhang, K. and Shen, Z.J. (2021) 'A systematic review of a digital twin city: a new pattern of urban governance toward smart cities', *Journal of Management Science and Engineering*, 6(2), pp. 125-134. Available at: <https://doi.org/10.1016/j.jmse.2021.03.003> (Accessed: 18 July 2022).
- Deniz, G.O. (2018) "Emerging CAD and BIM trends in the AEC education: an analysis from students perspective", *Journal of Information Technology in Construction*, 23, pp. 138-156. Available at: <http://www.itcon.org/2018/7> (Accessed: 27 July 2022).

BIBLIOGRAPHY

Deren, L., Wenbo, Y. and Zhenfeng, S. (2021) "Smart city based on digital twins", Computational Urban Science, 1(1), pp. 1-11. Available at: <https://doi.org/10.1007/s43762-021-00005-y> (Accessed: 29 June 2022).

Erwin, P. (1955) Meaning in the visual arts. 1st edn. Garden City, New York, U.S.: Doubleday Anchor Books, Doubleday & Company, Inc.

Esri (2021) ArcGIS: the foundation for digital twins. California, USA: Esri. Available at: <https://www.esri.com/en-us/lg/industry/infrastructure/arcgis-the-foundation-for-digital-twins> (Accessed: 29 June 2022).

Fan, C. et al. (2021) 'Disaster city digital twin: a vision for integrating artificial and human intelligence for disaster management, International Journal of Information Management, 56. Available at: <https://doi.org/10.1016/j.ijinfomgt.2019.102049> (Accessed: 22 July 2022).

Ford, D.N. and Wolf, C.M. (2020) "Smart cities with digital twin systems for disaster management, Journal of Management in Engineering, 36(4). Available at: [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000779](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000779) (Accessed: 22 July 2022).

Foucault, M. (1970) The order of things: an archeology of the human sciences. New York, U.S.: Pantheon.

Fuldauer, E. (2019) Smarter cities are born with digital twins, Tomorrow City. Available at: <https://tomorrow.city/a/smarter-cities-are-born-with-digital-twins#:~:text=In%20the%20realm%20of%20smart,movement%20of%20people%20and%20vehicles> (Accessed: 22 July 2022).

GE Healthcare Partners (n.d.) GE Healthcare command centres, Digital Twin. Available at: <https://www.gehccommandcenter.com/digital-twin> (Accessed: 18 July 2022).

Glaessgen, E.H. and Stargel, D. (2012) "The digital twin paradigm for future NASA and U.S. Air Force Vehicles", Honolulu, Hawaii, U.S.: American Institute of Aeronautics and Astronautics. Available at: <https://ntrs.nasa.gov/api/citations/20120008178/downloads/20120008178.pdf> (Accessed: 16 July 2022).

Gobeawan, L. et al. (2018) "Modelling trees for Virtual Singapore: from data acquisition to City6ML models, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, pp. 55-62. Available at: <https://doi.org/10.5194/isprs-archives-XLII-4-W10-55-2018> (Accessed: 25 July 2022).

Grieves, M. (2006) Product lifecycle management: driving the next generation of lean thinking. New York: McGraw-Hill Education.

Grieves, M. (2011) Virtually perfect: driving innovative and lean products through product lifecycle management. Florida, U.S.: Space Coast Press.

Grieves, M. and Vickers, J. (2016) "Origins of the digital twin concept". Available at: <https://doi.org/10.13140/RG.2.2.26367.61609> (Accessed: 17 July 2022).

Grieves, M.W. and Vickers, J.H. (2017) 'Digital twin: mitigating unpredictable, undesirable emergent behaviour in complex systems', in Transdisciplinary Perspectives on Complex Systems. Springer International Publishing, pp. 85-113.

Gutierrez, A.A. et al. (2021) "Wildfire response to changing daily temperature extremes in California's Sierra Nevada, Science Advances, 7(47). Available at: <https://doi.org/10.1126/sciadv.abe6417> (Accessed: 2 August 2022).

Hebei Xiongan New Area planning outline (2018). CPC Hebei Provincial Committee and the People's Government of Hebei Province. Available at: http://www.xiongan.gov.cn/2018-04/21/c_129855813_9.htm (Accessed: 26 July 2022).

Henderson, K. (1991) "Flexible sketches and inflexible databases: visual communication, conscription devices, and boundary objects in design engineering, Science, Technology, & Human Values, 16(4), pp. 448-473. Available at: <https://doi.org/10.1177/016224399101600402> (Accessed: 25 July 2022).

Ignatius, M. et al. (2019) "Virtual Singapore integration with energy simulation and canopy modelling for climate assessment, IOP Conference Series: Earth and Environmental Science, 294(1). Available at: <https://doi.org/10.1088/1755-1315/294/1/012018> (Accessed: 25 July 2022).

BIBLIOGRAPHY

Japan Economic Foundation (2009) Japan's cultural economy in a globalising world, Japan Economic Foundation, 2, pp. 26-29. Available at: https://www.jef.or.jp/journal/pdf/167th_cover08.pdf (Accessed: 2 August 2022).

Jasanoff, S. (2004) 'Ordering knowledge, ordering society', in *States of Knowledge: The Co-Production of Science and the Social Order*. 1st edn. Taylor & Francis (International Library of Sociology), pp. 13-45.

Latour, B. (2004) 'Why has critique run out of steam? From matters of fact to matters of concern', *Critical Inquiry*, 30(2), pp. 225-248. Available at: <https://doi.org/10.1086/421123> (Accessed: 25 July 2022).

Lau, N.-C. and Nath, M.J. (2014) 'Model simulation and projection of European heat waves in present-day and future climates', *Journal of Climate*, 27(10), pp. 3713-3730. Available at: <https://doi.org/10.1175/JCLI-D-13-00284.1> (Accessed: 2 August 2022).

Liceras, P. (2019) Singapore experiments with its digital twin to improve city life, *Tomorrow City*. Available at: <https://tomorrow.city/a/singapore-experiments-with-its-digital-twin-to-improve-city-life/> (Accessed: 25 July 2022).

Metropolis Magazine (2006) Smart city 2020. Available at: <https://metropolismag.com/programs/smart-city-2020/> (Accessed: 1 August 2022).

Moore, J.A. (2015) 'Emerging trends and opportunities in planning and design: integrating GIS, BIM and other technologies', *Real Estate Review*, 44(2), pp. 11-22.

Mott Macdonald (n.d.) Digital twins: better outcomes from connected data. Croydon, United Kingdom: Mott Macdonald. Available at: <https://www.mottmac.com/download/file?id=37140&isPreview=True> (Accessed: 13 July 2022).

National Park Board (2022) Singapore, a city in nature. Available at: <https://www.nparks.gov.sg/about-us/city-in-nature> (Accessed: 2 August 2022).

National Research Foundation (2021) Virtual Singapore. Available at: <https://www.nrf.gov.sg/programmes/virtual-singapore> (Accessed: 12 July 2022).

Obi, T. and Iwasaki, N. (2021) 'Smart government using digital twin in Japan', in 2021 International Conference on ICT for Smart Society (ICISS), pp. 1-4. Available at: <https://doi.org/10.1109/ICISS53185.2021.9533190> (Accessed: 28 July 2022).

Panofsky, E. (1939) *Studies in iconology*. New York, U.S.: Oxford University Press.

PLATEAU (n.d.) PLATEAU by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT). Available at: <https://www.mlit.go.jp/plateau/> (Accessed: 28 July 2022).

Pomeroy, J. (2020a) 'Introduction', in *Cities of Opportunities*. 1st Edition. London, UK: Routledge, p. 2-3. Available at: <https://doi.org/10.4324/9781003022299>.

Pomeroy, J. (2020b) 'The rise of the digital economy and its impact on the smart city', in *Cities of Opportunities*. 1st Edition. London, UK: Routledge, p. 190-205. Available at: <https://doi.org/10.4324/9781003022299>.

Pomeroy, J. (2011) *Idea house: future tropical living today*. ORO Editions.

Pyatkova, K. et al. (2019) 'Flood impacts on road transportation using microscopic traffic modelling techniques', in M. Behrisch and M. Weber (eds) *Simulating Urban Traffic Scenarios*. Cham: Springer International Publishing, pp. 115-126.

Qi, Q. et al. (2021) 'Enabling technologies and tools for digital twin', *Digital Twin towards Smart Manufacturing and Industry 4.0*, 58, pp. 3-21. Available at: <https://doi.org/10.1016/j.jmsy.2019.10.001> (Accessed: 16 July 2022).

Rasor, R. et al. (2021) 'Towards collaborative life cycle specification of digital twins in manufacturing value chains', in *The 28th CIRP Conference on Life Cycle Engineering*, Jaipur, India, March 10 — 12, 2021, pp. 229-234. Available at: <https://doi.org/10.1016/j.procir.2021.01.035> (Accessed: 25 July 2022).

BIBLIOGRAPHY

Ricci, A., Croatti, A. and Montagna, S. (2021) "Pervasive and connected digital twins – a vision for digital health", IEEE Internet Computing. Available at: <https://doi.org/10.1109/MIC.2021.3052039> (Accessed: 18 July 2022).

Rosen, R. et al. (2015) "About the importance of autonomy and digital twins for the future of manufacturing", 15th IFAC Symposium on Information Control Problems in Manufacturing, 48(3), pp. 567-572. Available at: <https://doi.org/10.1016/j.ifacol.2015.06.141> (Accessed: 18 July 2022).

Sacasas, L.M. (2020) "The analog city and the digital city, The New Atlantis, (61), pp. 3-18. Available at: <https://www.jstor.org/stable/26898497> (Accessed: 26 July 2022).

Saracco, R. (2019) 'Digital twins: bridging physical space and cyberspace', Computer, 52, pp. 58-64.

Siemens Healthineer (2019) Siemens Healthineer, digitalising healthcare: solutions for individual patients. Available at: <https://www.siemens-healthineers.com/perspectives/mso-solutions-for-individual-patients.html> (Accessed: 18 July 2022).

Singh, M. et al. (2021) 'Digital twin: origin to future', Applied System Innovation, 4(2). Available at: <https://doi.org/10.3390/asi4020036> (Accessed: 16 July 2022).

Singh, M. et al. (2022) 'Applications of digital twin across industries: a review', Applied Sciences, 12(11). Available at: <https://doi.org/10.3390/app12115727> (Accessed: 18 July 2022).

Smart Dublin (n.d.) Future planning: 3D data modelling. Available at: <https://smardublin.ie/future-planning-with-3d-modelling/> (Accessed: 25 July 2022).

Solman, H. et al. (2022) 'Digital twinning as an act of governance in the wind energy sector', Environmental Science & Policy, 127, pp. 272-279. Available at: <https://doi.org/10.1016/j.envsci.2021.10.027> (Accessed: 25 July 2022).

Stanford Engineering (2020) Digital twin for construction, Center for Integrated Facility Engineering. Available at: <https://cife.stanford.edu/Seed2019%20DigitalTwin> (Accessed: 12 July 2022).

Tao, F. et al. (2018) 'Digital twin-driven product design, manufacturing and service with big data, The International Journal of Advanced Manufacturing Technology, 94(9), pp. 3563-3576. Available at: <https://doi.org/10.1007/s00170-017-0233-1> (Accessed: 17 July 2022).

Vaughan, L. (2007) "The spatial form of poverty in Charles Booth's London, in The Spatial Syntax of Urban Segregation. London, UK: Elsevier (Progress in Planning), pp. 231-250. Available at: <https://doi.org/10.1016/j.progress.2007.03.001> (Accessed: 26 July 2022).

Wang, X.V. and Wang, L. (2019) Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0", International Journal of Production Research, 57(12), pp. 3892-3902. Available at: <https://doi.org/10.1080/00207543.2018.1497819> (Accessed: 22 July 2022).

Wataya, E. and Shaw, R. (2019) 'Measuring the value and the role of soft assets in smart city development, Cities, 94, pp. 106-115. Available at: <https://doi.org/10.1016/j.cities.2019.04.019> (Accessed: 9 July 2022).

White, G. et al. (2021) A digital twin smart city for citizen feedback', Cities, 110. Available at: <https://doi.org/10.1016/j.cities.2020.103064> (Accessed: 12 July 2022).

White, G., Liang, Z. and Clarke, S. (2019) "A quantified-self framework for exploring and enhancing personal productivity", in 2019 International Conference on Content-Based Multimedia Indexing (CBMI), 4-6 September, pp. 1-6. Available at: <https://doi.org/10.1109/CBMI.2019.8877475> (Accessed: 18 July 2022).

Wong, F.K.-H. (2019) Xiong'an New Area: President Xi's dream city, China Briefing. Available at: <https://www.china-briefing.com/news/xiongan-new-area-beijing-tianjin-hebei/> (Accessed: 27 July 2022).

World Economic Forum (2022) Digital twin cities: framework and global practices. Available at: https://www3.weforum.org/docs/WEF_Global_Digital_Twin_Cities_Framework_and_Practice_2022.pdf (Accessed: 25 July 2022).

Zou, Y. et al. (2021) "Urban planning as a way to pursue quality-oriented urbanisation: anatomy of the urban planning of Xiong'an New Area, China", Journal of Urban Affairs, pp. 1-16. Available at: <https://doi.org/10.1080/07352166.2021.1974304> (Accessed: 26 July 2022).

ACKNOWLEDGEMENTS

Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam dquatect atintur, ommosant Corepe nusandunt quid ut a et et

Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam dquatect atintur, ommosant Corepe nusandunt quid ut a et et

Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam dquatect atintur, ommosant Corepe nusandunt quid ut a et et

Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam quatect atintur, ommosant Corepe nusandunt quid ut a et
et Qui core nobit fugit quatiunt lab in prat la saperibus quo blaut idic tem quid eum enis reicae
sitiume maion nonet ma poritet quam dquatect atintur, ommosant Corepe nusandunt quid ut a et et

