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Towards National Connected Digital Twins - A Geospatial Perspective

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Abstract

Digital Twins are realistic digital representations of the physical world, frequently characterised by a two way link between digital and physical. Originating in manufacturing, they are now expanding to city and national scales. In this paper we explore connections between Geographic Information Science and National Digital Twins. Six different viewpoints and perspectives are presented on the topic, highlighting the importance of: geospatial data engineering; metadata engineering; standards; challenges facing mapping agencies; governance and public values; and a "reality check" that explores the gaps between what is required and what can currently be achieved. We present 22 recommendations and summarise the findings by presenting a high level research agenda to enable better understanding and articulation of the link between the two.

1. Introduction

Digital Twin (DT) are a "realistic digital representation of existing assets, processes or systems in the built or natural environment" (Callcut et al., 2021). They have a "bi-directional connection to the real asset, process or system and contain a way of computationally analysing incoming information to generate valuable insights for [..] specific use-cases." Twins should not be thought of as a product - they are an on-going process (Callcut et al., 2021). The human dimension - how humans interact with Twins - is also fundamental (Agrawal et al., 2023). Twins must (Bolton et al., 2018): have a purpose - in particular public benefit; value creation and provision of insight into the built environment; be trustworthy - including the importance of data quality, security and openness; function effectively - be based on a standard, connective environment, clear ownership and governance, be able to adapt as society evolves.

DT have gained widespread deployment within manufacturing (over 49% of DT, Lamb (2019)). More recently, they have emerged in other application domains, in particular the built environment and evolved to encompass natural systems (Section 2.1). While some Twins may be able to operate in isolation (i.e. as a closed system) there are interdependencies between many Twins - the built and natural environments are closely linked.

Thus, a system-of-systems approach (Section 2.2) is required to ensure that the links between systems are also considered. This requires "creating an ecosystem of connected digital twins - a National Digital Twin - which opens the opportunity to release greater value" (Gemini Papers, n.d.). Exploring the roots of system-of-systems concepts could provide some insight as to how to approach this challenging fragmentation. Rinaldi et al. (2001) note that system-of-systems interdependencies can include physical, cyber and also geographic. While normally geographic proximity has no impact (e.g. water pipes and gas pipes can co-exist under a street), an event such as a road collapse, explosion or flood can impact multiple systems at the same time (Rinaldi et al., 2001).

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Modelling these types of location-aware interdependencies is at the core of geospatial science. Concepts such as binary topological relationships (adjacency, intersection, disconnectedness), proximity, distance measurement, buffering, multi-scale representation in 2D and 3D and network analysis all lend themselves to this challenge (Section 2.4). The overlap between interconnected DT and geospatial concepts is further highlighted when we consider components of a DT (Sharma et al., 2022): the physical asset; the digital asset (i.e. the Twin); a continuous bidirectional relationship between them (the links between the two); internet of things components for sensing; data; analysis including machine learning; data security. Twin developers face the same challenges as geospatial scientists - siloed or inaccessible data (Bill et al., 2022), security, ethics (Goodchild et al., 2022) and real time data management (Errami et al., 2023).

1.1 This Paper

Given these initially theoretical but now increasingly practice-based overlaps between geospatial science and DT, our motivation in this paper is to contribute to advancing the concept of National Digital Twins by exploring the links between the two.

To start to unpick these challenges, EuroSDR[1] organised an AGILE workshop on 13th of June 2023 in Delft. The workshop gathered twenty participants from diverse backgrounds. Six experts from the geospatial domain were invited to present their views on the key challenges facing National DT. This was followed by break-out sessions to elicit additional viewpoints.

This paper first presents an overview of related concepts, then summarises the individual viewpoint, highlighting recommend-

[1] A not-for-profit organisation linking National Mapping and Cadastral Agencies with Research Institutes, Universities and Companies in Europe `https://eurosdr.net/`

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ations for further work - i.e. a research agenda. These are then coupled with insights gained during workshop activities to present a high level overview of the challenges ahead.

2. Background

This section first reviews individual (self contained) applications of DT, focussing on the built and natural environment. Links between these Twins are then explored via system-of-systems concepts, leading towards the concept of a National Digital Twin, and preliminary commonalities between National DT and geospatial science identified.

2.1 Digital Twins in the Built and Natural Environment

Applications in the built environment include (Shahzad et al., 2022): smart cities applications such as traffic management, congestion and carbon emissions reduction; evaluation of designs; compliance checking against sustainability or building regulations; requirements gathering;construction site progress monitoring; facility management. Lamb (2019) add energy-related and maritime applications to this list, and Agnusdei et al. (2021) focus on the safety domain of mobility systems, civil infrastructure, aeronautics, energy systems.

Within the natural environment, a systematic review by Maimour et al. (2024) mentions DT relating to mountains, wildlife, wetlands, river basins, oceans, forests air and floods. They also note, however, that natural environmental DT are as yet underdeveloped as they raise different challenges to built environment DT (Maimour et al., 2024).

2.2 Systems of Systems - Linking Digital Twins

“A system is a connected collection of interrelated and interdependent parts; a complex whole that may be more than the sum of its parts.” (Schooling et al., 2021). Systems of systems are ”large scale integrated systems which are heterogeneous and capable of independently operable on their own but are networked together for a common goal” (Jamshidi, 2017). Arsing from infrastructure, a system-of-systems approach helps to address the strong interconnections between infrastructure sectors such as water, transport, energy and waste (Hall et al., 2016). As Rinaldi et al. (2001) notes, a power failure impacts water pumps and hence manufacturing and homes, as well as rail - and hence supply chains.

As a whole infrastructure systems can be best analysed at a national scale (Hall et al., 2016). Individual systems naturally have a spatial extent Hall et al. (2016) and while the basis of a system-of-systems approach is physical assets, the ultimate end result is an impact on people and society.

2.3 National Digital Twins

The Centre for Digital Built Britain (CDBB) - set up to deliver a ‘National Digital Twin”- define such a twin as ”an ecosystem of connected digital twins to foster better outcomes from our built environment” (CDBB National Digital Twin Programme, n.d.). Originating in the built environment (and in particular via infrastructure projects) the concept is slowly evolving to span the natural environment - e.g. Henriksen et al. (2022) present the concept of a National Twin relating to climate change, combining hydrological modelling and information about the built environment. More broadly, Lamb (2021) note that the built environment relies on nature for resources, water, air and recreation; changes in the built environment also directly impact the natural environment and given the current ”climate and nature crises, we cannot continue to think about the built and natural environment as independent from one another.”

Additionally, the human dimension of National DT is fundamental to address issues relating to: fragmentation and silo-isation across different segments of society (Nochta et al., 2019), for governance and implementation (Nochta et al., 2019), and to maximise their potential to address some of society’s key challenges - e.g. across the United Nations Sustainable Development Goals (AlAmir, 2022; Hassani et al., 2022; Tzachor et al., 2022). The CDBB echo this concept in their ”Flourishing Digital Systems” paper, noting the importance of delivering desirable outcomes for people and the wider environment, as well as the importance of digitalisation and a cyber-physical infrastructure to deliver value from the built environment (Schooling et al., 2021). Taking the Twin-society links a step further, Tomko and Winter (2019) propose the concept of a cyber–physical–social system to represent the close coupling between the digital, physical and social environments.

2.4 Geographical Concepts for National Digital Twins

Geographical Information Science is the ”branch of information science that deals with the geographical domain, or the set of fundamental scientific questions raised by geographical information and the technologies that collect, manipulate and communicate” (Goodchild, 2011). Duckham et al. (2023) define a Geographical Information System (GIS, software that implements the science) as a ”computer-based information system that enables the capture and modelling, storage and retrieval, communication and sharing, manipulation and analysis, presentation and exploration of geographically referenced data”.

The diversity of software architectures for DT noted in a review by Broo et al. (2022) makes it challenging to provide a direct mapping between the agreed definition of a GIS and the components of a DT. However, similarities can be observed in the inclusion of an interaction layer that includes 3D representation, data visualisation, analytics, service management and system administration as well as a ’back end’ architecture that includes databases (i.e.”storage”) and data API (”retrieval”) (Broo et al., 2022). An alternative offered by Lu et al. (2020) includes data acquisition (”capture”), data modelling (”modelling”), a service layer (”manipulation and analysis”) and a top level of ’interaction with people’ (”presentation and exploration”).

Very similarly to DT, GIS are used by stakeholders to underpin local, citywide, regional, national and international decisions relating to healthcare, retail, transport, the natural environment, flood defences, travel, agriculture and many more (Longley et al., 2015). More broadly location supports the integration of different systems together and geographic information has a capacity to ground a system of systems as in the next generation Digital Earth vision (Goodchild et al., 2012).

3. Perspective 1 - Geospatial Data Engineering for Digital Twins - A Call to Action

Data is a key component of any DT; broadly three types of data can be identified: (Elsehrawy et al., 2021):

- Reference data: static blueprints, computer-aided design (CAD) drawings and 3D models of the building struc-

tures; documentation of mechanical, electrical and plumbing systems or other representations of their functional dependencies; and asset catalogues
- Transactional data: semi-static information about the status of assets and maintenance work orders, such as the condition inspection and date of assets.
- Time series data (from sensors) updated very frequently to give a near real-time status of the building

Data sources can include sensors (e.g. LiDaR, remote sensing, but also traffic, transport tickets, air quality), 3D models (city models, Building Information Modelling), demographics and statistical data and much more. All of these sources are familiar to geospatial professionals, although we may perhaps consider 'reference' data as transactional - for example, a 3D city model may be updated on a regular basis - in other words, a geospatial scientist acknowledges that the physical world changes through time - it is just that "time" may range from millennia (e.g. geology) through centuries and decades (changing city scales) right down to seconds (air quality).

A second key component of a DT is data science – the analytical component of the Twin that takes the incoming data and turns it into information for decision makers. Increasingly this involves machine learning and artificial intelligence. However, there is a problem – a shortage of data scientists. The UK's Quantifying the UK Data Skills Gap (2021) report notes that there were up to 234,000 data related vacancies that year.

This shortage is made much worse as up to 80% of a data scientist's time is spent doing data engineering (Muller et al., 2019; Mons, 2018) – finding, accessing, formatting and structuring incoming data to a point where they can use it for analysis. More formally, data engineering is defined as – "the development and maintenance of systems and processes that take in raw data and produce high quality consistent information that supports downstream use cases" (Reis and Housley, 2022). Two changes are needed to make this vision a reality:

- Data engineering is not new – spatial data infrastructures have existed for many years now. However, very little attention is paid (or funding allocated) to this aspect of DT. **Recommendation 1:** *to enable future Twins, we need to prioritise and re-focus DT efforts away from AI and machine learning.*
- **Recommendation 2:** *we also need to take a 'geospatial first' approach to data engineering* – at the moment, searching for data is text based so you can't find related data for the same location easily, interoperability involves joining text fields rather than spatial joins which are often the only option, and we are not taking advantage of our expertise natural map-based aggregation ('generalisation') to build connected DT at regional and national scale

Using a geospatial data engineering approach is particularly powerful given that most city and national data can be associated with a map location at some level of granularity (either directly or indirectly). **Recommendation 3:** *to achieve the above, we also need to understand the geographical hierarchy of National Twins* will it correspond to the familiar building/street/neighbourhood/town/municipality/region/country or will different (nested? overlapping?) geographies be required?

4. Perspective 2 - Metadata Engineering for the National Digital Twin

Metadata convey information necessary for different data engineering tasks including: discovering available data and tools, selecting the most relevant resources for a current goal, retrieving them, using them, and being informed about the possible gaps between the data and the depicted reality, publishing results back for other users to discover, for example in a perspective of coupling twins together, processing the result to generate a visual representation adapted to the end user experience.

All these tasks can present a high level of complexity. Potentially relevant data can belong to different domains, in different formats. There is no single technology but rather different options that need to be considered, such as spatial analysis, statistics, deep learning, graph processing, requiring specific expertise to define the appropriate tool and workflow.

Services can assist these tasks if tractable metadata exists about datasets, tools and processes. This in turn depends on interoperable, cross domains and expressive metadata standards and also on metadata production workflows. Yet, despite the development of such metadata standards, current metadata are quite poor, little documented and very often not tractable enough to support tasks beyond simple discovery (Zrhal et al., 2021). **Recommendation 4:** *we believe an approach is needed so that metadata production can be encouraged by metadata usage - i.e. metadata engineering for National Digital Twins.*

Grounding a decision on a DT requires access to uncertainties associated with the DT. To assist in this, quality-related metadata for the discovered data should organised in four categories : specification (a.k.a. product scope), quality criteria documenting the gap between datasets and the scope in terms of completeness, accuracy and consistency, provenance (a.k.a. lineage) and usage. However pdf documents and csv files prevail, published on web portals, usually in local language, and various files names.

Knowledge graphs have developed on the Semantic Web precisely to support the retrieval of resources adapted to a user context (Hogan et al., 2021). They encode knowledge about the object of interest, e.g. restaurants in London, to interpret a user query and propose appropriate content, to identify similarities between users to make further recommendations. They have been adopted in the domain of geodata to develop "Question Answering" capacities to assist users with no GIS skills in triggering GIS workflow (Xu et al., 2023). **Recommendation 5:** *a National Digital Twin Knowledge Graph should embrace the user domain (perhaps via Wikidata as a core common-sense vocabulary as in Zrhal et al. (2021)). It should also embrace the domain of resources - i.e. data sources, tool and should include connection between these domains.*

User feedback is valuable both for other users and for data providers, but its production and discovery is disorganised. The Geospatial User Feedback (GUF) standard from the Open Geospatial Consortium (OGC) can be an opportunity to do so (Zabala et al., 2021). **Recommendation 6:** *A benefit of a National DT Knowledge Graph would be to connect together the different experts who process data into this ecosystem to consolidate their expertise related to data quality and usability.*

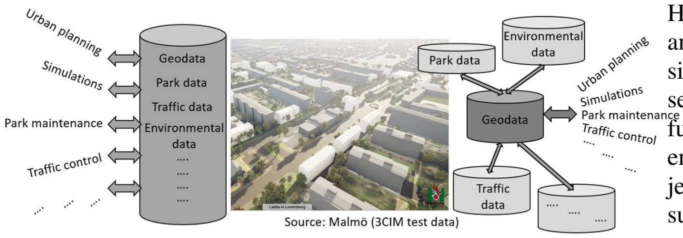

Figure 1. Illustration of a semantically rich standard (left) and a semantically thin standard (right).

5. Perspective 3 - Standards for Digital Twins

To create DT it is important to have standards that facilitate storage and retrieval of data from different sources to be used within a wide range of applications. Open standards for semantic 3D city models, such as CityGML and CityJSON, can be used to facilitate the creation and modelling of DT. In the recently released CityGML version 3.0, modules have been added for better support of versioning and time-series data (such as data from sensors). Furthermore, the standards can be extended (e.g. CityGML Application Domain Extension; ADE) to support different applications or to create national profiles of the standard. **Recommendation 7:** *explore the use of CityGML and ADE to create 3D data profiles for National DT*

A main consideration when creating a standard for a DT is what to include. One extreme approach would be to develop a standard (information model) that includes “everything” that is needed for a DT (Figure 1 left). That would result in a standard that is semantically very rich and it will probably be near to impossible to implement tools for the standard. In addition, to maintain the data stored in e.g. a database to keep it up-to-date would be a major challenge since cities are dynamic with constant changes and flow of data.

Another extreme would be to exclude (almost) all semantics and only include geometries with metadata about data collection and accuracy and a unique ID in the standard (Figure 1 right). The semantics could be stored in external databases and/or operational systems and linked to the objects in the DT via the unique IDs. That way the data could be stored and maintained closer to the source, e.g. at the traffic office or park management office, but it requires an efficient way of connecting to external sources and linking data.

One example of a national profile of CityGML, that in longer term will support the creation of digital twins, is the new Swedish specification for 3D city models called 3CIM (Uggla et al., 2023). This project was iteratively developed via workshops and tests, and takes the second of the above approaches - geometry metadata are aligned with the NMA’s framework to make it easier for cities/municipalities to create data according to 3CIM. **Recommendation 8:** *a thin specification - with separate geometry and semantics - may help to overcome challenges relating to data search and formats.*

6. Perspective 4 - Organizational Challenges Facing Mapping Agencies

Recommendation 9: *National Mapping Agencies emerge as natural candidates for spearheading the development of digital twins of territories, due to their production and dissemination of spatially referenced data.* This data can feed these intricate system-of-systems.

However, the demands for data quality, encompassing updates and levels of detail, pose huge challenges which could necessitate in-depth reorganization. Indeed, the prevalent model observed in most national or regional mapping agencies involves furnishing comprehensive and homogeneous geospatial reference data across their operational territories, following the trajectory of traditional cartographic productions. Traditionally, supplementary data enhancements for specific applications are made by other stakeholders, including public agencies at various administrative levels, private operators on their own initiative, or acting on behalf of public entities. For example, this could involve the integration of satellite imagery or extensive tree census data with official geo-data for effective city greening management.

Recommendation 10: *explore whether cartographic agencies are equipped to address the aforementioned challenges in terms of production, quality, standardization, and human resources?* Should they retain, if applicable, the monopoly on generating reference geospatial data, or should novel models be conceived? This query becomes particularly pertinent in the context of developing digital twins for cities, wherein the collaboration between municipal agencies, cartographic entities, and private actors assumes diverse configurations.

Three main trends (Figure 2) in the metamorphosis of the role of national cartographic agencies can be identified:

- “Keep it as usual”: National and regional agencies adapt their production methodologies to meet the requisites of digital twins, without significant alterations in collaboration frameworks with other stakeholders. However, there exists a risk of inadequately addressing identified challenges due to resource and human capital constraints.
- ”Promote Municipal/Territorial Level”: Digital twins for urban or territorial landscapes are managed at alternative authority levels (city, region, etc.), closer to the application and utilization spheres. Collaboration with mapping agencies and the private sector is envisioned from these echelons. Yet, the substantial risk persists of being unable to surmount all challenges owing to resource and expertise deficiencies. Greater delegation to the private sector introduces potential risks to public sovereignty, data control, and sensitive processes.
- ”Reshaping of Roles of Public Mapping Authorities (PMA)”: Intensifying collaboration among public authorities (national, regional, and municipal). This transcends the realm of mere technical challenges, encompassing sociotechnical considerations. Such an approach could strike a harmonious balance with private partners, safeguarding public sovereignty and ensuring control over data and processes. Nevertheless, it demands overcoming resistance to change from public operators and may evoke political and governance intricacies. This paradigm might constitute the optimal approach for inclusive citizen involvement throughout the entire process.

Preliminary work via a partnership to investigate and prototype a digital twin of Liege was launched in 2022 between the City of Liège, Liège University, the Liège Economic Redeployment Group (GRE-Liège) and public land development office (SPI). This highlighted the difficulty to prototype the third approach of reshaping PMA roles without firstly promoting the city level and addressing the governance issues. **Recommendation 11:** *explore whether a ”keep it as usual”, promote municipal/territorial level” or ”reshaping of the roles of PMA” is an* *appropriate strategy for national mapping agencies to engage with DT, along with related governance issues.*

7. Perspective 5 - Governance and Public Values

In the context of an urban DT, three types of reality must be considered: physical reality, social reality and digital reality. Paradigms already exist to study the links between these realities as illustrated in Figure 3. **Recommendation 12:** *the Digital Twin should be a triple and connect physical, social and digital realities together*. Urban and National Digital Twins are made up of the sum of many (Urban) Digital Twins, in a distributed and decentralised fashion. Each of the twins have their own area of focus: either community, topic or physical area.

Today, there is still too much focus is on the traditional and "smart" city - whilst our lives are mostly affected by the changes in the Social and Digital Reality (social media is well known, but also AI, AR/VR, Web3 will have a large impact on our daily lives). From a legislative perspective, there is a gap between social and physical reality.

An important milestone to achieving the Urban Digital Twin is to improve general awareness that digital is not solely an instrument but is part of the reality. This is an on-going process with debates regarding the ownership and governance of platforms that play a critical part in urban processes. **Recommendation 13:** *National Mapping Agencies are needed to promote Open Urban Platforms that can be shared by public and private actors.* Such Open Urban Platforms represent a more adapted solution than all private platforms or all public platforms.

National Mapping Agencies have long managed the foundational content for digital representation of the physical reality, traditionally in 2D, increasingly in 3D. They also play a role in the ethical use of that digital representation in combination with the real-time feedback from the physical city. They have vast experience in achieving interoperability through the use of international Open Standards and are looked upon to provide technological leadership in their implementation. **Recommendation 14:** *validate whether National Mapping Agencies can be the guardians of an Interoperable DT*.

Recent Digital Acts from the EU provide a first framework for the creation of Digital Twins in alliance with European public values. **Recommendation 15:** *the Digital Twin must be made and managed and benefited from by both the private and public sector, academic community and especially the citizens themselves*. This will help to avoid both full private control (e.g. social media) and full public control ('big brother').

8. Perspective 6 - A Reality Check

The locational aspects of national and city-level DTs is crucial when addressing sustainable issues. GI-science has therefore a lot to offer to the implementation of DTs. However, while theoretically potential is high, there are many GI-related challenges still to be tackled to fulfil the promises of nationwide DTs that is able to address and solve global challenges.

8.1 A catch-all term: risk to ignore fundamental problems

The term Digital Twin lacks a uniform definition. The risk of a such a catch-all term is that research can focus on just a part of the DT (mostly technical) and ignore more complex fundamental issues, working on isolated parts of the problem. **Recommendation 16** *clarify the meaning of the term Digital Twin*. fundamental research challenges about collecting, sharing and integrating multi-temporal, multi-resolution heterogeneous data across organisations, scales and domains still remain and are easily overlooked by a term that covers all and nothing.

8.2 Going beyond the concept of an exact mirror

The exact mirror concept of a DT representing reality works for a single product that can be isolated from its surroundings such as a car or a plane, but not for a complex, interconnected reality of our physical environment. GI modelling is always based on an abstraction of the world where selections and generalisations are applied to capture reality in geographical data. Different data views on the same reality exist just as different DTs exist depending on focus, scale and purpose. **Recommendation 17:** *determine how to develop and implement a multi-view (multi-scale, multi-temporal) DT concept*.

8.3 Temporal data

To enable the two-way flow of information from the physical to the virtual model and back, realtime data and continuous updating of the DT is required. However, for geo-data an update cycle of days or weeks is often already high. **Recommendation 18:** *determine how "real-time" is real-time and what temporal data is needed for a National DT.*

8.4 Versioning

Recommendation 19: *address the challenge of how to maintain and manage different versions of geodata*. This allows users to be able to go back to a version of the data on which a decision was based or to study trends of specific phenomena, noting that the underlying data models also change with time.

8.5 Simulation National DTs

On the fly simulations are considered an important part of a DT from which it can directly be seen what the impact of a specific intervention is on different aspects such as noise, air quality, mobility, energy etc. However, most types of simulations require sophisticated hardware and specific data structures as input. Simulation outputs are also easily confused with predictions at a certain moment in time. **Recommendation 20:** *how to use the same DT-basis for a wide variety of simulations and how to feed back the simulation results into one integrated view, including usable uncertainty information.*

8.6 Realism versus realistic

Often it is thought that the more real the DT looks the better. But realistic looking models are not per se realistic models of reality. These models can be outdated, contain errors and be equally (sometimes even less) accurate than less detailed models, while they are more expensive to acquire and to keep up to date. At the same time, many simulations require thinning and generalisation of the data to reduce performance issues. **Recommendation 21:** *determine how to specify and accommodate (create, manage, align) different levels of detail and different accuracy levels for the same reality for different needs.*

8.7 Practice readiness of DTs

To understand the practice-readiness of DTs it is helpful to locate the current state of the implementation of nationwide and

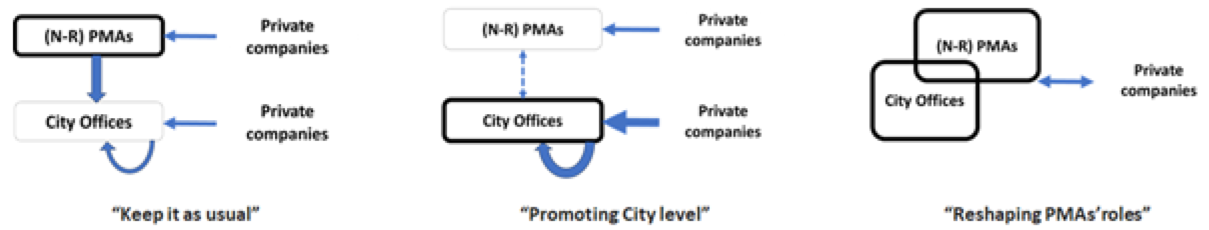

Figure 2. Data flow and Articulation between PMA and private companies in the three main approaches

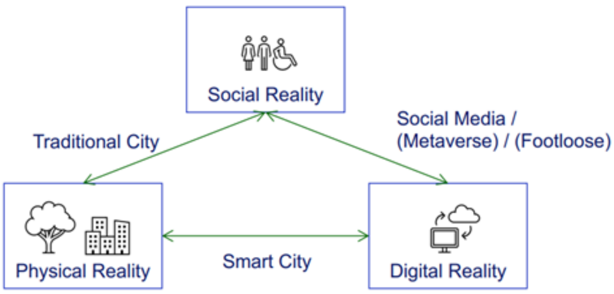

Figure 3. The Urban Digital Twin is a Triple

city level DTs on the Gartner hype cycle (Linden and Fenn, 2003). The concept of national and city-level DTs can be placed somewhere between the Innovation trigger and the Peak of Inflated Expectations. To date, studies have shown the (mainly technical) potential of location Digital Twins which has led to high, and often inflated expectations.

Recommendation 22: *More exemplars are required that convert results and insights from pilots into feasible DT implementations.* This will help us understand how fundamental GI science challenges can be addressed in order to implement the full concept of National DT. To reach the Plateau of Productivity DT should solve real-world problems within available budgets and within organisational and institutional structures.

9. Integrating the Perspectives

The concept of a National Digital Twin is an adaptation of the manufacturing vision where a group of relevant experts and operators interact with a digital counterpart of a manufactured physical component and use it to agree on a possible intervention, to simulate it on the digital counterpart, to evaluate its impact and ultimately improve the physical component. Here, the manufactured physical component is replaced by territory in all its complexity. Agreeing on a possible intervention is replaced by making a decision for our future and tooling the ecological transition, for example deciding to move a whole set of housings from a threatened seashore to a secure location, or informing in real time citizens about what source of energy to use.

However, for the most part, geospatial solutions to these challenges concentrate on one aspect of the process. This fragmentation is reflected in the DT community, where (Shahzad et al., 2022) note that even the development of city-level digital twins is at a conceptual stage, and better integration of DT with associated digital technologies (IoT, Industry 4.0, Big Data) is required.

Recommendations from the six perspectives above are coupled with additional insights identified through workshop break-out sessions to develop a high level research agenda. Related recommendation numbers given in brackets.

9.1 Identify the Components of a (National) Digital Twin (16)

As noted in Section 2.4 there is as yet not a clear definition of the components of a Digital Twin. To date, we understand that a National DT:

- will not be a monolith but will be a connected series of Twins (following the system-of-systems approach outlined in Section 2.2).
- will encompass multiple scales - from neighbouhoods to national extents
- will link the built environment, the natural environment and society
- will focus on societal and other benefits

A preliminary list of components generated during the workshop includes: 3D city models, simulation, interoperability, meeting citizens' expectations, metadata, people, standards, data ethics, diversity and inclusion, metadata, governance, education, data and reference data.

We can speculate that the components of a National DT will be identical to those of city or urban DT, but it will be important to explore this in more detail. We do no yet understand whether a National Twin will be solely a question of interconnecting existing twins or also of designing additional Twins specifically for territories. It is unclear whether the concept of a National DT will in fact be the same or similar across multiple countries.

The lack of clarity on the components of a National DT renders the task of identifying where geospatial expertise can contribute to making this integrated vision a reality more challenging.

9.2 Exploit and Publicize Existing Data, Metadata and Standards and Related Expertise (1,7,9,20)

The geospatial community's data expertise covers: 3D (3D models, virtual reality, 3D), Spatial Data Infrastructures (governance, ownership, reference data, up-to-date data, interoperability, standards, data integration, system architecture, metadata, workflow, management, public), ethics (diversity & inclusion, public values, data ethics, citizen expectations), Users/application (users/target group, education, people, citizen expectations, privacy), simulation/models is of great relevance to National DT, in particular when it is considered that this expertise frequently relates to national (or even cross-border) datasets. Standards within the community are also relatively mature, and adaptable to meet National DT requirements. Data expertise spans the built environment, the natural environment and human geography.

However, this expertise is perhaps not well known or understood outside the community: National DT developers are not able to benefit from the expertise and data providers and geospatial scientists are not able to demonstrate value.

9.3 Further Develop Multi-Scale and Temporal Data Methods and Expertise (3,17,18,19,21)

National Mapping and Cadastral Agencies are world leading experts at deriving less detailed (smaller scale) data from large scale data, through generalisation. This mirrors the 'scaling-out' of a National DT as component DTs are linked. Data versioning across time is also well understood - the physical environment is undergoing continual change, and map update cycles are relatively short. This basis provides an ideal foundation for the requirements of a National DT. We can speculate - based on a preliminary exploration of system-of-systems concepts (Section 2.2) - that geospatial concepts (topological relationships, network analysis, buffering and many more) will be crucial in identifying potential inter-dependencies between Twins.

9.4 Developing New Tools and Approaches (2,5,6,8,12)

From a technical perspective, geospatial science is a very well established (50+ years) discipline. The required tools and approaches identified above - new approaches to metadata, knowledge graphs, Twins as triples, alternative data architectures, geospatial-first approaches - are not specific to National Digital Twins. It remains to be seen if further work is also required to handle as-yet-unrecognised technical challenges.

9.5 Addressing Societal Challenges (15,22)

Applying DT at territorial scale sets up strong expectations both from the technology providers and from stakeholders, and case studies are fundamental in terms of managing these. A National Digital Twin needs to represent not only physical reality but also society and needs to be able to communicate with citizens and practitioners. To engender the required trust, it may be the case that the Twin should be created and hosted somewhere authoritative rather than within the private sector.

9.6 Understanding the Role of National Mapping Agencies (10,11,13,14)

Linking to the above, it will be important to understand the role, readiness and business models that geospatial organisations such as National Mapping Agencies and international organisations (e.g. EuroSDR) will play in developing a National DT. Answers to the above challenges, coupled with an understanding of business drivers, will help to clarify this situation.

9.7 Building a National Digital Twin - Learning Together

The bias in the research agenda outlined here should be noted. Recommendations have been identified by incorporating the viewpoints of six geospatial experts with those of others attending a EuroSDR workshop associated with the AGILE international Geographical Information Science conference. The majority of the recommendations relate to data, perhaps identifying data-related issues as a priority whose resolution will enable other challenges to be addressed.

The challenges listed perhaps highlight the current disconnect between those developing National Digital Twins and the geospatial community - our community may lack an understanding of the system-of-systems approaches that drive National Digital Twins, of IoT and the specific complex, big data, AIdriven analysis that forms the heart of many Twins, in particular when the strictest definition of a DT - two-way real-time data feeds and automated decisions - is considered. Geospatial experts struggle to articulate the benefit of our approach in a National DT context, and to articulate value. Equally, it could be speculated that the DT community - while making use of geospatial approaches - are perhaps doing so implicitly, and thus perhaps not exploiting geospatial data to its fullest extent or with full awareness of any inherent quality issues or consequences of misapplying geospatial techniques. Addressing these skills and knowledge gaps should be a priority.

Going forwards it will also be important to incorporate the perspectives of other stakeholders - e.g. infrastructure operators, central government, software vendors and many more - as well as to provide examples and case studies to illustrate the practical applications of the emerging recommendations.

10. Conclusion

A National DT encompasses not only specific entities, like a dam or an infrastructure but also entire territories. This paradigm is driven by strong expectations from administration to be assisted to face the climate crisis and social crises with the territories they administer, from local to national levels - a DT of territories is seen as a solution to take back control of the impact a local administration and citizens have on their territory. An important difference from many classical DT applications is that territorial twins should not assist in maintaining territories but rather they should assist in engaging a transition, in other words assist societies to decide the future they want to reach for their environment and how to reach it. At national levels, countries are developing National Digital Twins strategies to articulate territorial DT development with public value, trust and regulation. In a context where phenomena do not stop at borders and where some impacts need to be evaluated at a global scale, the DT concept can also be applied to multi-country challenges and to the Earth as a whole.

"A strong ecosystem of connected digital twins should connect processes, technology and organisations to deliver positive outcomes for people, society and nature by making better decisions, faster." (Gemini Papers, n.d.). Ensuring that geospatial and DT practitioners are open to the idea that there is learning to do on both sides, and that it will be beneficial to combine forces and work towards a common goal is fundamental. We very much need to engage with disciplines beyond our own to progress the research agenda outlined here, and ensure that the vision for a National DT becomes a reality.

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