Conceptualising value in public sector geospatial information for digital twins

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Keywords: Digital Twins, Value, Public Sector Geospatial Information, NMCA, Conceptual Analysis

Abstract

Digital twins (DTs) are digital representations of physical entities where data connections synchronise the physical and digital states at a specified frequency. While DTs originated in manufacturing and aerospace, they are increasingly applied at geographic scales addressing urban issues. As a result, DTs must utilise geospatial information (GI) to represent the built environment, though this is often an implicit aspect. Public sector geospatial information (PSGI), typically produced by National Mapping and Cadastral Agencies (NMCA) is a particular type of GI that serves as an authoritative, foundational component to geospatial applications. However, the value of this PSGI as foundation component of DTs is not well understood. Existing GI valuation methodologies do not account for the unique characteristics of foundational PSGI, or its role within DTs , leaving NMCAs unable to justify investment, and adapt their contributions, to emerging DTs. To address this gap, this study applies Jabareen’s (2009) conceptual framework analysis methodology to define what value means in the context of PSGI in DTs. The analysis identifies seven value enablers and five value dimensions that characterise PSGI value in DTs and provide the basis for future quantitative valuation methodologies. These concepts are integrated through an urban infrastructure DT example and synthesised through boundary case analysis. The resulting conceptual understanding enables NMCAs to systematically articulate and evidence their contributions to DTs.

1. Introduction

A Digital Twin (DT) is a digital representation of a target entity (including components, assets, systems or processes) with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronisation (ISO, 2023). Having been initially conceptualised to address challenges and inefficiencies in closed systems in aerospace and manufacturing sectors (Kritzinger et al., 2018), DTs have since evolved to address multifaceted, multi-system issues at geographic scales such as urban planning (e.g. Seto et al., 2023; Caprari et al., 2022; Abdeen et al., 2023), infrastructure management (e.g. Bolton et al., 2018; Lu et al., 2020) and environmental monitoring (e.g. Wedi et al., 2025). In these cases, the convergence between physical and digital states may be achieved not only through automated data flows but also via human-in-the-loop processes such as expert judgement, model calibration and participatory inputs. DTs create value through improving efficiency, management and productivity, though DT implementations rarely comprehensively assess the value realised (Abbas et al., 2024).

DTs which now exist at geographic scales to solve complex urban problems, must now integrate geospatial information (GI) to, at the very least, provide the location foundation upon which other discipline-specific, data streams are built (Ellul et al., 2024). This location foundation, which may include digital surface models (DSMs), building footprints, and network data, is often produced and distributed by NMCAs as Public Sector GI (PSGI). However, as Metcalfe et al. (2024) highlights, the geospatial aspects of DTs are often not stated, and therefore risk being undervalued. This underscores an observation made by Kruse et al. (2017) that the intrinsic value of GI is often implied, leading the science of measurement to fall behind. In this paper, we use public sector *geospatial* information (PSGI) as the primary term to align with contemporary use, while recognising that earlier GI economics literature uses the closely related term public sector *geographic* information.

As GI becomes an increasingly important DT component, NMCAs face difficulties articulating their value contributions and therefore obtaining funding because their PSGI is embedded within complex systems and hard to attribute separately from other inputs (Longhorn and Blakemore, 2007). Existing GI valuation methodologies, such as the UK’s Geospatial Commission 7-step theory of change approach (Geospatial Commission, 2022), therefore do not adequately address PSGI’s role as foundational infrastructure in DT contexts, creating a need for a conceptual framework that clarifies what value means in this setting, prior to adapting or developing new valuation methodologies for PSGI in DTs.

1.1 Aims and Research Questions

This study progresses these issues by contributing a conceptual framework describing what value means in the context of PSGI in DTs, addressing the following research question:

- What are the defining characteristics and enablers of PSGI value contribution to DTs?

This framework enables NMCAs to systematically articulate and evidence their contributions to DTs, and to inform future approaches to valuing PSGI in DT contexts, but does not aim to fully quantify PSGI’s contribution.

2. Background

2.1 The Geospatial Foundation of DTs

DTs are now being applied to address issues at geographic scales such as that of a city, infrastructure network, an entire

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-XI-4-2026-331-2026

country or even continental and planetary scales (Ali et al., 2024; Wedi et al., 2025). As national-scale authorities, NMCAs bear responsibility for geospatial data provision across entire countries, including regions beyond major metropolitan areas. This national mandate ensures more equitable geospatial coverage than private or city-focused data providers, supporting infrastructure, governance, and service delivery decisions across diverse geographic and institutional contexts — a foundational role particularly important as DTs scale beyond pilot implementations. These geospatial foundations provide the interoperable, multi-scale reference required for dynamic, integrated DT architectures in which other disparate data from Internet-of-Things (IoT) devices and other sources are integrated (Jeddoub et al., 2023; ANZLIC, 2019), such as building footprints, surface models and networks. These datasets encode not only geometry but also rich semantics which are critical for interoperability and meaningful integration of heterogenous DT components. While the illustrative example in Section 4.4 focuses on an urban infrastructure DT, the conceptual framework is intended to apply at national and supra-national scales.

2.2 The Conceptual Basis of Value for PSGI

Value is often used in the context of costs and benefits. For clarity, costs denote the resources requirement for PSGI production, maintenance and governance while benefits denote the positive outcomes arising from PSGI use in DTs. Value, then, represents the broader significance attributed to those outcomes (Longhorn and Blakemore, 2007).

Valuing data, particularly GI, is challenging due to its intangibility and unique attributes. GI is often indexed by a single location attribute, which can obscure the fact that it also contains rich thematic and relational information. This complicates separating its contribution from other dataset components. Its value is context-dependent (varies by user, application, and context), present only when used and, in terms of costs, it is costly to produce but cheap to reproduce (Barr and Masser, 1996; Longhorn and Blakemore, 2007).

PSGI is considered a public good and therefore exhibits non-rivalrous use (its utilisation does not diminish availability) and non-excludable provision (access cannot be restricted), which creates value through network effects and spillover benefits (i.e. beyond the direct user of the PSGI) (Kruse et al., 2017; Longhorn and Blakemore, 2007).

In terms of value types, the main distinction is between exchange value (financial recovery) and use value (benefits from application). While use value encompasses socio-economic, environmental, functional, hedonic, and epistemic (knowledge-based) dimensions (Sweeney and Soutar, 2001; Fallis, 2004; Haddadi et al., 2016). These generic value dimensions provide a conceptual starting point for inductively deriving a relevant set of PSGI-in-DT specific value types from the literature sample (See Section 4.2). In this paper we focus primarily on use value, understood as the benefits realised when PSGI is applied in DTs, while recognising that exchange value (e.g. fees, licensing income) and costs (e.g. production, maintenance, ecological footprint) are also relevant. We aim to characterise how PSGI contributes to public value creation in DTs, rather than to compute a single monetary value.

2.3 Limitations of existing GI valuation methodologies

While various methodologies have been developed to assess GI value, each exhibit limitations in the context of PSGI in DTs. Cost-benefit analyses (CBA) and value of information (VOI) studies require explicit monetisation and well-defined scenarios, problematic for foundational PSGI realised indirectly in downstream applications. These methods lack frameworks for isolating PSGI's location component, capturing spillover effects, or addressing option value (Coote et al., 2017; Bernknopf and Shapiro, 2015). The theory of change (ToC) approach proposed by the UK's Geospatial Commission in 2022 is advantageous by assessing qualitative benefits and complex causal relationships, but fundamentally relies on articulating these clear causal links which is challenging in a foundational PSGI context, given how implied and deeply embedded these data are likely to be (Geospatial Commission, 2022).

There is a need to adapt these methodologies to address the challenges of PSGI in DTs. However, prior to this, a conceptual understanding of value in the context of PSGI and DTs is necessary.

3. Methodology

This study adapts Jabareen's eight-phase conceptual framework analysis methodology to systematically define PSGI value in DTs (Jabareen, 2009). Jabareen's methodology is a grounded, qualitative approach that constructs conceptual frameworks by iteratively coding and clustering concepts across multidisciplinary literatures. It emphasises flexibility and the identification of relationships and boundaries among concepts rather than formal hypothesis testing. It has previously been applied, for example, to develop the Resilient City Planning Framework in urban governance contexts (Jabareen, 2013), demonstrating its applicability to geospatial-infrastructure domains. This precedent, combined with the methodology's emphasis on iterative refinement and its capacity to synthesise disparate disciplinary perspectives, makes it particularly appropriate for defining PSGI value in DTs, an issue spanning geospatial science, infrastructure theory, public policy, information economics, and digital twin development. Jabareen's original methodology comprises eight iterative phases from mapping data sources, identifying and deconstructing concepts, to integrating, synthesising and validating them.

Using Jabareen's methodology, we adapt the method into six steps tailored to the PSGI-in-DT context: (Step 1) identifying and categorising data sources; (Step 2) defining value concepts; (Step 3) deconstructing value concepts; (Step 4) integrating value concepts in an example; (Step 5) synthesising the conceptual framework; and (Step 6) validating the conceptual framework. Each of these steps are carried out in Section 4.

Given limited literature directly addressing PSGI value in DTs, an inferential approach is used in step one, where necessary, to identify value concepts. The literature is categorised into one of six types which were defined based on the nature of the inference: (1) Direct (PSGI in DTs) - studies that explicitly address PSGI use in DTs; (2) Direct (PSGI/DTs) - studies that explicitly examine the value of PSGI or DTs independently; (3) Logical extension - studies examining value in another related context (e.g. geographic information systems (GIS), spatial data infrastructure (SDI), Building Information Modeling (BIM)) where principles can be logically extended; (4) Implicit DT demonstration - studies or industry reports highlighting a DT implementation that demonstrates, but does not necessarily explicitly deal with PSGI; (5) Theoretical foundation: foundational theoretical frameworks that provide ways of understanding relevant value generation mechanisms applicable to PSGI in DTs; (6) Policy framework - government strategies, standards, or policy documents that articulate the value of PSGI.

4. Conceptual Framework Development

Section 4 operationalises the six adapted steps of the conceptual framework analysis, progressing from source identification to defining value, specifying value enablers, integration in an example case, synthesis of the analysis, and validating the results.

4.1 Step 1: Identifying and Categorising Data Sources

The literature sample was obtained from Google Scholar using searches such as (”public sector geospatial information” OR ”public sector geographic information” AND ”value”), (”digital twin” AND ”urban” AND (”geographic OR ”geospatial information) as well as forward and backward citation searches. Google Scholar was selected because it indexes peer-reviewed articles, reports and policy documents across multiple disciplines relevant to PSGI value in DTs. The literature sample was selected based on: relevance to one or more of the six literature types and being written in English. Reports and public policy documents were also included in the search. Twenty-one studies were selected:

- **Direct (PSGI-DT)**: Ellul et al. (2022, 2024) (2)
- **Direct (PSGI)**: Coote et al. (2017); Kruse et al. (2017); Longhorn and Blakemore (2007);Ho et al. (2018); (4)
- **Direct (DT)**: Jeddoub et al. (2023)); Qi et al. (2021) (2)
- **Logical Extension**: Bernknopf and Shapiro (2015)); Zuiderwijk et al. (2014); Lu et al. (2020); Kolbe et al. (2005) (4)
- **Implicit DT Demonstration**: Hopfstock et al. (2022); Schrotter and Hürzeler (2020); Seto et al. (2023); Wedi et al. (2025); Hayes et al. (2022); Gobeawan et al. (2018) (6)
- **Theoretical**: Star (1999); Moore (1997); Rajabifard and Williamson (2002) (3)
- **Policy framework**: Department for Science, Innovation and Technology (2023) (1)

This literature sample provides the basis for inductively defining PSGI value concepts in Step 2.

4.2 Defining Value Concepts

Five value types emerge from assessing PSGI context in the literature sample: (1) Economic, (2) Functional, (3) Societal, (4) Environmental, and (5) Knowledge-based. These five types synthesise and somewhat aggregate the broader socio-economic, environmental, functional, hedonic and epistemic dimensions introduced in Section 2.2. For example, societal relates to socio-economic and public value aspects, while knowledge-based relates to epistemic value. These types are analytically discinct but not mutually exclusive. A single DT implementation may realise multiple types of value simultaneously.

4.2.1 Economic Value from PSGI in DTs Inferring the economic dimension of PSGI value in DTs highlights effiency and productivity improvements alongside cost savings from the enablement of geospatial data integration. Coote et al. (2017) provides empirical evidence for this, demonstrating through cost-benefit analyses that 3D geospatial data investments in the UK generate measurable economic returns through reduced data duplication, improved planning efficiency and comprehensive infrastructure asset management. While not directly relating to DTs, 3D geospatial data is often considered an important component of DTs (Ali et al. (2024) and therefore, Coote et al. (2017), establishes baseline economic returns that are relevant to PSGI in DTs. In addition to this, Bernknopf and Shapiro (2015) provide a comprehensive framework showing quantifiable benefits through uncertainty reduction. Hopfstock et al. (2022), describing the national DT implementation in Germany, demonstrate economic value through multi-domain DT integration where geospatial foundations enable simultaneous and cost-effective visualisation across diverse urban systems. Zuiderwijk et al. (2014), from the open data perspective, provide empirical evidence of measurable corporate and public sector value through innovation, diversification, and operational efficiency. Collectively, these sources establish three economic value inferences for PSGI in DTs which are direct cost reduction in planning and asset management, improved decision-making under uncertainty, and network effects enabling multiple simultaneous applications.

4.2.2 Functional Value from PSGI in DTs The enabling role of PSGI allowing DTs to operate as coherent integrated systems across multiple domains represents functional value aspects of PSGI. Ellul et al. (2024) argue that GI requirements underpin national connected DT architectures, providing standardised spatial reference frameworks that enable interoperability (Jeddoub et al., 2023; Kolbe et al., 2005). Schrotter and Hürzeler (2020) show implicit functional value through the Zurich DT integration of 3D models, networks, and simulations dependent on geospatial connectivity. Hopfstock et al. (2022) document multi-domain DT integration where standardised geospatial foundations enable coherent analysis across transportation, environmental, and infrastructure domains. Foundational infrastructure theory, described in Star (1999) provides the theoretical grounding that value derives not from infrastructure itself but from services it enables, a principle directly applicable to PSGI’s role in DTs. Rajabifard and Williamson (2002) establish that PSGI functions as foundational infrastructure enabling systemic coordination. Wedi et al. (2025) demonstrate the vision for global-scale integration of earth observation data with computational models and Qi et al. (2021) emphasise data integration as prerequisite for DT operational capability. Together, these sources establish that functional value emerges through the capacity of PSGI to stabilise spatial reference frames and semantic models, enable data integration across heterogeneous systems, support physical-digital synchronisation, and facilitate multi-domain applications operating on unified spatial foundations.

4.2.3 Societal Value from PSGI in DTs Inferring PSGI value in DTs from a societal perspective reveals public outcomes including safety, inclusivity, transparency, democratic participation, and innovation. Public value theory, introduced in Moore (1997), establishes that government agencies derive legitimacy through demonstrable contributions to societal well-being which underpins the societal contributions of PSGI from NMCAs. The UK Geospatial Strategy operationalises this through policy emphasising geospatial data’s role in citizen engagement, democratic accountability, and evidence-based decision-making Department for Science, Innovation and Technology (2023). Gobeawan et al. (2018) provides implicit demonstration through an application supporting the placement of trees to improve quality-of-life, modelled based on geospatial foundations. Destination Earth (Wedi et al., 2025), aligned with United Nations (UN) Sustainable Development Goals (SDG) and European climate objectives, demonstrates a global-scale societal focus. Rajabifard and Williamson (2002) and Qi et al. (2021) establish that data infrastructure and integration are prerequisites to enable societal coordination at scale in DTs. Collectively, these sources infer that societal value could emerge through PSGI-enabled DTs supporting evidence-based policy, transparent decision-making, inclusive stakeholder participation, improved safety and resilience, and service delivery.

4.2.4 Environmental Value from PSGI in DTs The literature suggests that PSGI use in DTs could result in environmental value through resource optimisation, sustainability monitoring, carbon accounting, and environmental forecasting in climate adaptation and sustainable development contexts, while recognising the environmental costs through the ecological footprint of digital infrastructures themselves. Lu et al. (2020) establish frameworks for resource optimisation and environmental assessment through DT implementations applicable to PSGI in DTs. Gobeawan et al. (2018) demonstrates implicit environmental value through enabling analysis of vegetation in urban environments, flood risk modelling, and green infrastructure planning dependent on authoritative 3D GI. As implicit demonstrations, Hayes et al. (2022) refers to environmental value through geospatial-based climate hazard modelling, enabling adaptation planning. Destination Earth (Wedi et al., 2025) targets global-scale climate forecasting and extreme weather prediction. Rajabifard and Williamson (2002) establish foundational data infrastructure requirements enabling environmental benefits. Collectively, these sources establish that environmental value emerges through enhanced capacity to model complex systems, forecast impacts, enable transparent environmental monitoring, and support evidence-based adaptation policy.

4.2.5 Knowledge-based Value from PSGI in DTs Finally, knowledge-based value is inferred from the literature as the ability of foundational PSGI to reduce uncertainty and stabilise knowledge through authoritative reference coordinates, standardised classifications, and quality-assured datasets establishing shared ontologies that diverse stakeholders can trust. Kruse et al. (2017) state how geospatial reference data reduces positional uncertainty and stabilises spatial frameworks essential to reliable decision-making. Bernknopf and Shapiro (2015) show how geospatial data stabilises knowledge and enables confident choices under ambiguous conditions, with direct applicability to DTs where authoritative spatial reference reduces modelling uncertainty. Hopfstock et al. (2022) (Digital Twin Germany) demonstrate standardised GI providing stable ontologies and shared reference systems enabling interoperability. Ho et al. (2018) highlight 3D PSGI as an enabler of improved perception of quality of public services. Destination Earth (Wedi et al., 2025) demonstrates knowledge-based value through standardised Earth observation data for authoritative global environmental monitoring. Rajabifard and Williamson (2002) show that foundational SDI do not only support access and coordination, but create a shared knowledge environment whereby stakeholders can exchange and apply GI consistently across sectors. Similarly, Qi et al. (2021) emphasise that DTs depend on accurate, reliable and knowledge-rich data, including expert and fused data, to support understanding of complex system states. Kolbe et al. (2005) addresses semantic standardisation and ontologies enabling reliable cross-system interpretations through CityGML. Knowledge-based value emerges through PSGI’s role in establishing authoritative, quality-assured reference data that reduces spatial analysis ambiguity and provides trusted foundations for complex DT models. In DT contexts, this shared, authoritative geospatial and semantic foundation also enables the discovery of new cross-domain patterns and infrastructure interdependencies that would otherwise remain obscured, thereby supporting knowledge creation instead of only stabilising existing knowledge.

These dimensions interact dynamically within DT ecosystems, revealing that value is not singular but multidimensional, dependent on how PSGI is used in different DT applications. These dimensions provide the conceptual basis for identifying the core value enablers of PSGI value to DTs in Step 3.

4.3 Step 3: Defining the Core Enablers of PSGI Value Contribution

Four enabler themes with seven specific enablers affect PSGI value contribution to DTs were inductively identified from recurring mechanisms in the literature sample and from foundational infrastructure and SDI research (e.g. Star (1999); Rajabifard and Williamson (2002) (Table 1).

4.3.1 Accuracy Accuracy represents PSGI’s capacity to provide precise, validated spatial positioning and measurement that serves as a reliable common reference frame for DTs, representing how closely PSGI’s positional information represents the real world. This accuracy is maintained through ongoing quality assurance and update cycles, enabling multiple DT applications to depend on the same authoritative spatial foundation without requiring independent verification or risking errors. Although accuracy is closely related to broader data quality, we separate it here analytically to emphasise its critical role in the foundational common geospatial reference for DTs. In this way, accuracy is not merely a data quality metric; it is the structural foundation enabling PSGI to function as trusted infrastructure that multiple organisations and applications can build upon simultaneously. Broader data quality attributes are discussed separately in the context of Quality in Section 4.3.3.

4.3.2 Trust Trust as an enabler for PSGI value in DTs originates from its institutional character as a public good, governed transparently by NMCAs and accessible to all stakeholders without commercial restrictions. This public character generates network effects: as more organizations integrate PSGI, collective trust increases because each stakeholder knows others are depending on the same verified data. Interoperability standards such as CityGML (Kolbe et al., 2005) and INSPIRE (Bartha and Kocsis, 2011) as well as SDI frameworks operationalise this trust by ensuring PSGI follows consistent technical and quality protocols, enabling reliable automatic integration across diverse DT applications. Trust thus becomes structural infrastructure rather than dependent on individual relationships, creating conditions where multiple competing organizations can coordinate through shared PSGI foundations.

4.3.3 Quality PSGI’s quality enablers are characterised by positional accuracy (see Section 4.3.1), temporal currency, and thematic completeness. These quality attributes are underpinned by governance arrangements that give stakeholders confidence in using PSGI as a trusted input to DTs. This distinguishes PSGI from volunteered GI (VGI) or commercial dataset inputs and reduces the risk of error propagation through integrated DT systems. This creates conditions where diverse organisations can simultaneously depend on shared PSGI without requiring independent verification of its reliability. Regular update cycles mean that core PSGI is not static but evolves somewhat with the physical environment (temporal currency), enabling DTs to align sensor data to an up-to-date spatial framework. PSGI value is also enabled by retrospective capabilities through historical records and prospective value through option value for unforeseen applications (such as for autonomous vehicles). By enabling predictable, documented quality across time, PSGI transforms from a data product into trustworthy infrastructure that DTs can confidently reference as their common spatial foundation.

4.3.4 Fitness-for-Purpose PSGI enables heterogeneous information integration within a unified coordinate systems, creating non-linear value scaling as DT ecosystem maturity increases (Star, 1999; Lu et al., 2020). Virtual Singapore (e.g. Gobeawan et al., 2018) and CReDo (Hayes et al., 2022) demonstrate how single geospatial foundations simultaneously support environmental, emergency response, and planning without duplication. Spillover effects and positive externalities extend PSGI’s benefits far beyond direct users through methodological, informational, sectoral, and temporal spillovers where urban accessibility analysis becomes reference material for peer communities, utilities benefit from transportation investments through improved crew routing, historical PSGI enables longitudinal analysis benefiting future applications (Bernknopf and Shapiro, 2015; Hopfstock et al., 2022; Hayes et al., 2022).

4.4 Step 4: Integrating value concepts: An Urban Infrastructure DT example

Integration is demonstrated through a smart water infrastructure and flood management case study (based on Sabri et al. (2023)). This urban water and flood management DT is for a mid-sized city implementing water-sensitive urban design principles and serves here as an illustrative case of the broader PSGI-in-DT value mechanisms. This example illustrates how PSGI enablers operate together with the value concepts to generate multiplicative value across infrastructure domains.

The foundational infrastructure function is established through standardised, authoritative geospatial datasets: high-accuracy Digital Elevation Models (DEM), storm water catchment boundaries, 3D building models capturing roof areas and impervious surfaces, street network geometries, and parcel-level land use data. These datasets, maintained by an NMCA and freely accessible through an SDI, provide the spatial reference frame upon which the DT is constructed. Quality assurance mechanisms ensure positional accuracy consistent across measurement cycles, and temporal maintenance keeps the spatial foundation current as the city evolves through time.

Cross-domain integration becomes possible through a unified coordinate system enabling:

- storm water engineers to model flood pathways using Digital Surface Models (DSM),
- urban planners to assess green infrastructure interventions using land use and building geometries,

Spillover effects manifest through unexpected value realisation where historical PSGI enables:

- longitudinal trend analysis and climate adaptation planning,
- shared coordinate systems enable cross-sector analysis revealing infrastructure interdependencies previously invisible within domain-specific systems

Public good characteristics and network effects drive adoption because PSGI is openly accessible through SDI governance. Therefore no sector bears exclusive investment burden and each additional user or application increases value for all others. Quality enablers like accuracy, standards compliance and transparent governance create trust enabling simultaneous multi-organisational dependence on shared foundations.

This examples demonstrates that PSGI value in DTs is structural. It emerges through the interaction of all seven enablers (Section 4.3) operating together within an ecosystem of coordinated stakeholders and applications.

4.5 Step 5: Synthesising and making sense of the conceptual framework

This stage synthesises the conceptual framework through borderline and distinctive case analysis, clarifying what constitutes PSGI value contribution in DTs and what does not.

Borderline cases are those that may appear similar to PSGI in DTs but do not fully meet the definition. Volunteered Geographic Information (VGI) (Abdeen et al., 2023), such as OpenStreetMap (OSM) (Bennett, 2010), can provide a spatial framework and exhibit foundational characteristics, but lacks the authoritative quality assurance, accountability and public governance associated with NMCA-produced PSGI. In some jurisdictions, authoritative PSGI is released under open licenses and later ingested into platforms such as OSM. However, licensing decisions and long term governance remain with the originating public authorities, not OSM itself. Commercial GI products form a second borderline case where they may be more technically advanced in some contexts but differ in economic character because they are rivalrous, licenced and less stable as long term public infrastructure.

Distinctive cases are DT components that are essential, and sometimes appear foundational, but are conceptually separate from PSGI value. Sensor data, for example, may be positioned using NMCA coordinate systems and their outputs georeferenced but the value of the measurements themselves is distinct from the value of PSGI’s stable geometric and semantic foundation. Analytical algorithms and computational models are another distinct value source as they may consume PSGI as an input but generate value through modelling and computation rather than through the geospatial foundation itself. Visualisation platforms and user interfaces similarly may present PSGI content, but the software engineering value of dashboards or 3D rendering engines remains analytically separate.

These cases show that PSGI value to DTs is neither universal nor exclusive. Instead, it is a foundational form of infrastructure value that enables other components to create their own distinct contributions.

Theme	Core Enabler	Description
Accuracy (Geometric reference frame)	Foundational Infrastructure Function	PSGI provides the essential framework and geometric foundation built on positional accuracy upon which DT architectures are constructed, providing an anchor for dynamic information to a stable spatial structure.
Trust	Public Good Characteristics and Network Effects	PSGI exhibits public good properties generating cumulative value through network effects where increased usage enhances value but does not diminish availability for others.
	Interoperability, Standards and SDI Integration	PSGI value derives from adherence to rigorous quality and interoperability standards embedded within SDI that established organisational, policy and technical foundation.
Quality (Quality attributes and governance practices)	Quality	PSGI value is determined by quality attributes like positional accuracy, temporal currency, thematic completeness and national coverage which generate user trust and enable reliable decision-making in DTs.
	Temporal dimensions: historical context and option value	PSGI value encompasses retrospective capability through historical geospatial records and substantial option value for future DT use cases (e.g. autonomous vehicles) (often due to continuity of public funding).
Fitness-for-purpose	Cross-domain integration	PSGI enables analysis, visualisation, and decision-support capabilities that would not be possible without the geospatial foundation.
	Spillover Effects and Positive Externalities	PSGI generates value extending beyond direct users to broader communities, sectors and temporal scales through spillover effects.

Table 1. Value Enablers for PSGI Value in DTs

Prerequisite conditions and emergent outcomes further reveal the relational dynamics aspects of Jabareen's conceptual framework approach (Jabareen, 2009). Prerequisite conditions refer to the institutional, governance and technical conditions that must already be in place for PSGI value to DTs to be realised, while emergent outcomes refer to the broader operational, analytical and governance effects that arise once these enabling conditions and PSGI value mechanisms are present in practice. The four prerequisite conditions identified from the literature sample relate to the maturity of NMCA authority Bartha and Kocsis (2011), SDI policy frameworks Rajabifard and Williamson (2002), multidisciplinary stakeholder commitment Hayes et al. (2022); Gobeawan et al. (2018), and DT ecosystem readiness Qi et al. (2021); Kolbe et al. (2005); Jeddoub et al. (2023). The five emergent outcomes identified from the literature sample are reduced data duplication costs Coote et al. (2017), accelerated development Bernknopf and Shapiro (2015), insights on infrastructure interdependencies Ho et al. (2018); Hopfstock et al. (2022), governance innovation through multi-sectoral collaboration Hayes et al. (2022) and temporal data enabling both operational decision-making and long term adaptation planning Wedi et al. (2025); Seto et al. (2023).

4.6 Step 6: Validating the conceptual framework through empirical indicators

This step, similarly to the penultimate step in Jabareen's model, is to validate the conceptual foundations built in earlier stages through developing empirical indicators that can assess the presence and extent of each value dimension in operational DT contexts.

This section presents an initial set of observable indicators that illustrate how the PSGI value dimensions (identified from literature sample in Step 1) might be assessable in DT implementations (Table 2). At this stage, these indicators act as a structured checklist rather than a quantitative ranking tool, enabling flexible adoption across diverse DT implementations while providing a foundation for future development of more comprehensive methodologies.

These six steps are not strictly sequential but iterative, reflecting Jabareen's grounded theory methodology where conceptual understanding evolves through recursive engagement between data and framework. The definition of value enablers (Step 3) informed re-examination of value dimensions Step 2), revealing that enablers operate not as separate components but as integrated mechanisms enabling value realisation.

Value type enabled from PSGI in DTs	Example indicators
Economic value	Cost metrics (e.g. quantified duplication avoidance), development efficiency (e.g. time to implementation)
Functional value	Cross-domain integration metrics (e.g. number of sectors accessing shared PSGI), interoperability measures (e.g. reduced translation effort required) and application breadth from PSGI option value (e.g. number of new uses of PSGI emerging post DT implementation)
Societal value	Stakeholder (e.g. citizen) participation rates, cross-sectoral outcomes
Environmental value	Number of environmental analyses enabled
Knowledge-based value	Uncertainty reduction (e.g. confidence intervals narrowing), decision-maker confidence surveys

Table 2. Example measurable indicators for each value type enabled by PSGI use in DTs

The Urban Infrastructure example (Step 4) revealed additional conceptual nuances requiring boundary clarification (Step 5). Empirical indicators (Step 6) expose areas requiring framework rethinking (Section 5), particularly regarding how contextual factors like institutional maturity, SDI governance, stakeholder commitment shape value. This iterative, comparative approach between concepts and data is central to Jabareen's methodology and ensures the framework evolves with deeper analytical engagement Jabareen (2009).

5. Discussion

5.1 Defining Characteristics and Types of PSGI Value in DTs (RQ1)

PSGI providers like NMCAs are currently unable to reliably quantify their value contribution to DTs, resulting in challenges justifying investments and adapting to the proliferation of DTs at geographic scales. This study addresses this gap by applying a structured conceptual analysis to define enablers, types and prerequisites for PSGI value in DTs. The analysis identifies four enabling themes (accuracy, trust, quality and fitness-for-purpose) and five types of value that explain what makes PSGI valuable in a DT context. It also defines five distinct value dimensions (economic, functional, societal, environmental and knowledge-based) describing the different types of value that PSGI can create when integrated in DTs.

Building on established work on SDIs (Rajabifard and Williamson (2002)) and foundational geospatial infrastructures, a key contribution of this study is to systematise PSGI’s foundational role in DTs by specifying the enabling themes, value dimensions, prerequisite conditions and emergent outcomes through which this role manifests. This foundational role distinguishes PSGI from other data sources positioning it as a critical enabler of scalable DTs. The urban infrastructure DT model case demonstrates this where a single geospatial foundation simultaneously enables water management, transportation, planning and emergency responses.

Rather than claiming to have discovered PSGI’s foundational character, the framework in this study provides a DT-specific conceptualisation that NMCAs can use to structure how they articulate that role to policymakers and stakeholders.

5.2 Implications and Limitations of the Results

Existing GI methodologies that can be applied to PSGI, such as the cost-benefit analyses, VOI studies and ToC frameworks, only capture value for specific decisions but not for foundational infrastructure. Like other uses of PSGI, in DTs, the contribution of PSGI is difficult to isolate from that of other inputs such as domain data, sensor streams and models. In this study we do not attempt to quantify PSGI’s individual contribution but instead develop a conceptual framework to clarify the dimensions and enabling conditions through which PSGI contributes value to DTs.

Future PSGI valuation frameworks therefore can build on this conceptual foundation by distinguishing foundational from transactional value, developing indicators for network effects and spillovers, accounting for prerequisite conditions such as NMCA maturity, SDI, stakeholder commitment and DT readiness, and by using value type specific indicators rather than forcing all benefits into a single monetary metric.

The framework is limited by its focused literature base, its illustrative use of a single urban infrastructure example, and the fact that the proposed indicators (Table 2) have not yet been tested across multiple DT settings, scales and institutional contexts. Future work should therefore examine how these value mechanisms generalise to non-urban, regional and national DTs, including contexts with differently structured SDIs, and continue to search across both ”geographic” and ”geospatial” terminology given the inconsistency of their use.

6. Conclusions

As cities increasingly deploy DTs to address complex challenges such as flood management and infrastructure optimisation, the foundational role of PSGI remains largely implied. This study provides the first structured conceptual framework defining how PSGI value manifests in DTs.

Overall, the framework conceptualises PSGI as a public sector, public good infrastructure whose multi-dimensional use value in DTs spans economic, functional, societal, environmental, and knowledge-based dimensions. By making these dimensions explicit, it provides NMCAs with a more robust basis for articulating the value of, and prioritising, their investments in PSGI within emerging DT ecosystems. Ultimately, this allows NMCAs to better explain their role in DT ecosystems.

The key insight is that PSGI value is structural and multiplicative, creating a shared geospatial foundation that enables multidisciplinary integration beyond what individual datasets can achieve alone. PSGI from NMCAs is therefore not peripheral to DTs but critical to their capacity to address complex urban problems at scale.

Acknowledgements

The authors would like to thank Ordnance Survey and EuroSDR for supporting this research project.

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