

Comparative Practices in 3-D Geoinformation by National Mapping and Cadastral Agencies

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Abstract

The rapid evolution of three-dimensional (3-D) geospatial science has redefined the standards of national mapping and cadastral agencies (NMCAs). Traditionally bodies of authoritative 2-D topographic products, these organisations now face the challenge of producing, maintaining, and disseminating national-scale 3-D geospatial datasets that support applications ranging from climate adaptation and urban planning to disaster response and digital twins. This paper presents a comparative study of five NMCAs, comprising IGN (France), BKG (Germany), Kadaster (The Netherlands), GSI (Japan) and USGS (United States of America). By examining agency structure, economic models, and 3-D data collection programmes, this paper identifies converging trends in AI integration, national surveys, along with divergences in funding and implementation. The analysis highlights insights and potential lessons for organisations at early stages of national 3-D dataset implementation.

1. Introduction

Over the past two decades, national mapping and cadastral agencies (NMCAs) have undergone a gradual transformation from the production of two-dimensional (2-D) topographic maps to management of three-dimensional (3-D) spatial data infrastructures (LUX, 2024; Lukas et al., 2025). These agencies, traditionally focused on the generation and maintenance of authoritative national mapping products, are now required to produce and maintain consistent, interoperable, and updatable 3-D datasets that describe the real world in high spatial and semantic detail (Kedar, 2023). This transformation has been aided by technological advances in airborne LiDAR, photogrammetric computer vision, artificial intelligence (AI), and big data / cloud computing (Deibe et al., 2020), which together allow the capture and management of petabyte-scale datasets (Li et al., 2016; Yang et al., 2017), supporting more accurate, accessible, and interoperable spatial data infrastructures.

The demand for national-scale 3-D data reflects diverse societal needs. Governments require high-fidelity 3-D information for infrastructure management, flood modelling, and climate adaptation; cities use digital twins for urban planning, transport optimisation, and energy efficiency (MLIT, 2021); disaster management agencies depend on rapid 3-D mapping for emergency response; and research institutions exploit point cloud analytics for applications ranging from infrastructure management to environment legislation. Consequently, NMCAs now function as both data providers and service brokers, balancing technical innovation, financial sustainability, and governance responsibilities (Crompvoets and Broucker, 2015).

Global initiatives illustrate the scope and complexity of this transition. Europe's Digital Europe programme supports continental digital twin strategies, while EuroSDR promotes cross-border research and harmonisation (Streilein et al., 2017). In Asia, Japan's Project PLATEAU provides open 3-D city models to enhance disaster resilience (MLIT, 2021). In North America, the USGS 3-D Elevation Program (3DEP) delivers infrastructure construction and management, energy development, iden-

tification of critical minerals, hazard mitigation and response, emergency response, and management of natural resources (Lukas et al., 2025). These programmes highlight both the opportunities and challenges of implementing national 3-D data infrastructures.

Five NMCA case studies: IGN (France), BKG (Germany), Kadaster (Netherlands), GSI (Japan), and USGS (USA). These were selected to examine organisational structure, funding, 3-D topography programmes, AI utilisation, and digital twin creation. These agencies represent diverse national approaches to 3-D geoinformation integration, offering a globally balanced perspective across Europe, Asia, and North America. Through a scoping review combining case studies with thematic analysis, and drawing on recent NMCA organisational documents and online articles, the study identifies converging trends and persistent challenges across varied governance and funding contexts. The findings provide valuable lessons for organisations in the early stages of integrating 3-D geoinformation into national-scale production workflows. Monetary values are presented in their original national currencies, with approximate equivalents in US dollars (USD) provided for comparison, based on exchange rates at October 2025.

2. NMCA Case Studies

2.1 France: Institut National de l'Information Géographique et Forestière (IGN)

IGN is the French national mapping and forestry institute. It leads national 3D/topography collection predominantly through its LiDAR HD programme, publishes national 3-D products and toolkits, such as Myria3D, and coordinates research and European Union (EU) co-funded workstreams for a national digital twin. IGN also acts as the national standard setter and primary distributor of national geospatial products.

Funding combines state investment with regional partnerships, reflecting a decentralised governance style. Operational success

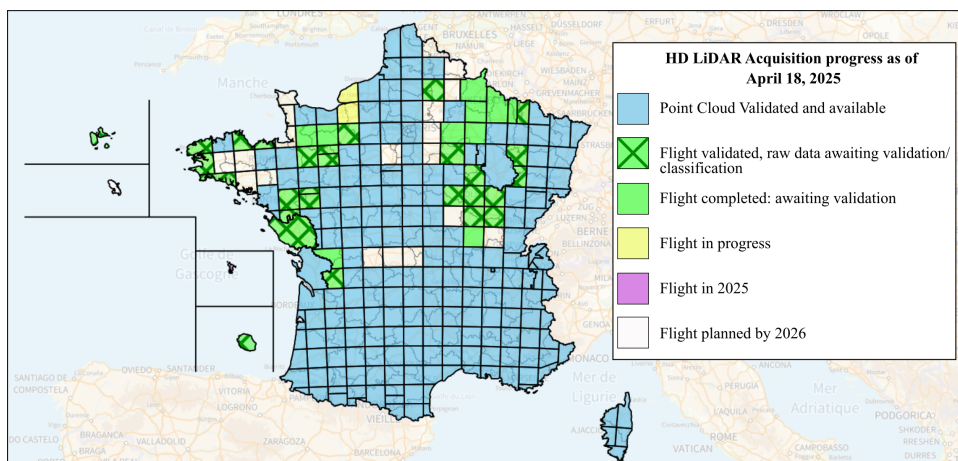


Figure 1. Progress of the LiDAR HD program across France and territories as of 18th April 2025. Edited from source (Macarte, 2025)

relies on extensive territorial partnerships, including collaborations with the Grand Est and Pays de la Loire regions, Corsica, and Charente-Maritime (IGNF, 2022). LiDAR HD (for “High Density”) (IGN, 2025), the national 3-D data collection programme is supported by both the state and the EU with a total of €57 million (\$66,224,310) over five years (Nachez, 2025).

In terms of data collection, LiDAR HD currently covers approximately 550,000 km² at an average point density of 40 pts/m² (points per square metre), generating around three petabytes of data (Zach, 2021; Roche, 2024). This has been carried out since 2021, with the aim to finish the entirety of France and its territories by 2026 (Gaydon et al., 2024). Figure 1 shows the acquisition progress as of early 2025.

In processing, IGN has developed Myria3D, a deep learning library that achieves up to 96% automation in semantic segmentation of point clouds, with precision and recall of 98% for buildings and vegetation classes (Roche, 2024). The integration of machine learning methods into IGN’s processing pipelines has enabled automated classification and feature extraction on massive datasets (Roche, 2024). IGN digital twin Pilot projects illustrate applications in heritage restoration, such as the Notre-Dame Cathedral reconstruction (Gros et al., 2023; LUX, 2024). Although specific to heritage, this project highlighted the importance of digital twins, as they represent the alignment of various disciplines (Tallman, 2024).

2.2 Germany: Bundesamt für Kartographie und Geodäsie (BKG)

BKG is the federal agency responsible for national cartography and geodesy of Germany. It is also a primary body for the Digital Twin Germany programme, providing federal coordination, specifications, and a platform to ingest state and municipal data, while acquisition is implemented as federated/contracted aerial surveys (commercial contractors) and state (Länder) datasets.

Germany’s national 3-D geoinformation work is federated. This means that data acquisition and initial production are performed largely by the federal states through their local surveying geoinformation agencies (Landesvermessungsämter), while BKG provides federal coordination, common specifications, national products and a harmonised, nation scale digital twin programme. In practice this creates a national mosaic (See Figure 2) made from state and local acquisitions that are integ-

rated, standardised and served at the federal level for cross-government use. According to the Federal Ministry of Finance, (BMF, 2025a), for FY2025, BKG received a budget of €85,347,000 (\$99,158,705), from the central government. The “Digital Twin Germany” project has then received a further €10 million (\$10,256,693) in 2025, with subsequent years planned to receive similar investments (BMF, 2025b). From 2021 to 2025, the “Connected Urban Twins” project, which focused on Hamburg, Leipzig and Munich, received an investment of €32 million (\$37,178,560)(Xu et al., 2023).

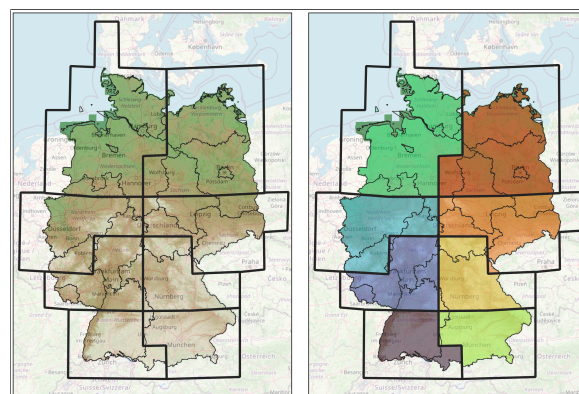


Figure 2. LEFT: Topographic Terrain Map of Germany. Right: Germany is divided into eight areas, which are used for outsourcing data collection. Data sourced from BKG (BKG, 2025) Mosaic extents source: (von Dömming, 2025).

The agency collaborates with federal states to deliver high-density LiDAR datasets exceeding 40 pts/m² (GIM International, 2025), with Hamburg piloting integration of LiDAR, cadastral, and infrastructure data using CityGML profiles for semantic interoperability (Gruber and Recklinghausen, 2020). Topographic data is also collected on a three-year update cycle (BKG, 2022). Classification combines deep learning and object-based image analysis to model land cover, buildings, and vegetation (Niemeyer et al., 2014).

BKG’s Digital Twin Germany project is approximately 50% complete as of August 2025 (GIM International, 2025). The digital twin functions as an intelligent 3-D representation, encompassing essential geospatial objects, supporting holistic mapping processes. Moreover, BKG has developed a technical platform that integrates AI, cloud computing, and big data technologies to enable complex analytical workflows without requir-

ing individual federal authorities to build separate infrastructures (BKG, 2022). The German Standard DIN Spec 91607 "Digital Twins for Cities and Municipalities", provides a framework for implementing urban digital twins. This provides a level of consistency at the national level (Connect Urban Twins, 2025).

2.3 Netherlands: Kadaster

Kadaster is the Netherlands' national land registry and geoinformation agency responsible for maintaining national registers, including the Register for Buildings and Addresses (BAG), and distributing data through Publieke Dienstverlening Op de Kaart (PDOK, Public Services on the Map). The Netherlands' national elevation programme, Actueel Hoogtebestand Nederland (AHN), is managed jointly by provinces and Rijkswaterstaat (Directorate General for Public Works and Water Management) and distributed by PDOK, providing national airborne LiDAR coverage. Kadaster and its open datasets, BAG and AHN, are the primary inputs used to create 3DBAG, the 3-D building model dataset.

Kadaster operates with a commercial fee-based cost-recovery model, though 25% of its €282.6 million (\$328,333,158) budget comes from the state (EuroGraphics, 2025). Kadaster's commercial approach demonstrates the viability of balancing public service obligations with revenue generation. The model provides sustainable funding for continuous 3-D data development and is particularly effective in the Netherlands' dense urban environment, where high-precision 3-D building data supports regulatory compliance, urban planning, real estate, and infrastructure applications.

A notable topographic collection programmes by Kadaster is AHN. This has been carried out in five phases; AHN1 (1997-2004) (Westerhof et al., 2023), AHN2 (2007-2012), AHN3 (2014-2019) (Shi and Kissling, 2024), AHN4 (2020-2022), and AHN5 commencing from 2023 (3DBAG-Pipeline, 2018). Although the start-stop dates are well documented, areas across the Netherlands vary. These repeated surveys have covered the entirety of the Netherlands (approx. 41,900 km²), with this reaching a total of 70 Terrabytes of raw point cloud data (Shi and Kissling, 2024). The specification for point density for AHN5 is given as 10 pts/m² minimum. However, AHN4 ranges from 20-30 pts/m² with an ASPRS (American Society for Photogrammetry and Remote Sensing) standard classification code (Shi and Kissling, 2024).

Innovation is reinforced by collaborations with universities and private partners. TU Delft research has advanced automated reconstruction workflows across multiple levels of detail (Dukai et al., 2020), enabling frequent national updates. The Netherlands3D digital twin framework reflects the country's preference for open-source, community-driven development, reducing costs and promoting rapid adoption (Netherlands3D, 2024).

3DBAG produces authoritative 3-D building models for the nation's 10 million buildings. The 3DBAG generation involves an automated 3-D building reconstruction process that fuses 2D building footprints (BAG) with height attributes extracted from Airborne LiDAR point clouds (AHN). The workflow isolates LiDAR points within each footprint, calculates key heights (e.g., ground, eave, roof height) using statistical methods like percentiles, and utilises planar fitting for roof segmentation.

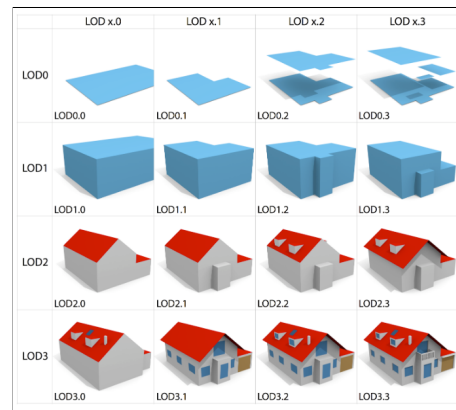


Figure 3. The Netherlands 3-D BAG programme: LoD variations based on 3-D BAG implementation (Peters et al., 2022).

This data is then used to extrude and regularise the 2D polygons into geometrically consistent, closed 3-D models, managed entirely by the open-source 3dbag-pipeline. (Delft, 2021; Peters et al., 2022). Open dissemination is maintained through the PDOK platform, which provides 3-D models of LoD (level of detail) 1.2, 1.3 and 2.2 (Figure 3). Furthermore, through val3Dity, all 3-D data is verified, removing the need for user assessment (Peters et al., 2022).

2.4 Japan: Geospatial Information Authority (GSI)

GSI is Japan's national mapping authority, which controls networks, elevation products, and datum maintenance. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) leads Project PLATEAU, Japan's national urban digital-twin initiative that defines the standard data product specification for 3-D city models and subsidises municipal 3-D model creation. Many prefectures/municipalities, private contractors, and research labs contribute data and models. Complementary providers supply high-resolution elevation meshes and satellite-derived DSM/DTMs for national and commercial use.

Japan's GSI strategy prioritises urban development, disaster management, and improving mobility and flow data (Uchiyama et al., 2025). Open access to 3-D datasets fosters public engagement. GSI is primarily funded directly by the central government, with supplementary budgets provided during fiscal years. The entire GSI body was provided a budget of ¥13.39 billion (\$86,587,078) for FY2025 (GSI, 2024). The PLATEAU project received a budget of ¥2.1 billion (\$13,579,751) for FY2023, and ¥4.82 billion (\$31,170,174) for FY2025 (GSI, 2022, 2024).

GSI are also moving towards a national topographic survey, entitled "3D Digital National Land Base Map". This aims to achieve full national coverage by FY2028 by aerial LiDAR (GSI, 2025) With a collection point density of more than 4 pts/m², each tile/file (km²) being 0.5 - 4 GB (GSI, 2025), and with the estimated size of Japan being 378,000 km², will result in a total of 756 to 1512 Terrabytes of data. GSI also integrates subsurface modelling, combining ground-penetrating radar with mobile mapping to analyse surface and subsurface features (Rodrigues Neto et al., 2024).

AI-driven methods, including recurrent neural networks and multimodal data fusion, support infrastructure monitoring and urban planning, enabling risk assessments that merge geological, hydrological, and built environment factors. Project

PLATEAU provides open 3-D city models that integrate seismic, hydrological, and demographic data to support preparedness and planning (Seto et al., 2023). Both the budget increase from FY2023 to FY2025 reflect GSI's and Japan's initiative to increase PLATEAU's extent, with the initial aim of publishing data for 250 cities (Uchiyama et al., 2025). Further studies (Yamashita et al., 2025), have shown the suitability of using digital twins for visualisation of earthquakes, with further aims to provide feedback to increase the resilience of cities.

2.5 United States: United States Geological Survey (USGS)

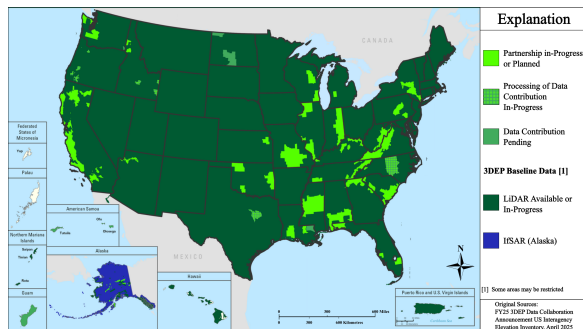


Figure 4. USGS 3DEP nationwide coverage achievement and partnership funding distribution (Edited from: USGS, 2025a).

The USGS is the federal lead for national elevation through the 3-D Elevation Program (3DEP) and its successor "3D National Topography Model" (3DNTM). USGS issues national specifications (LiDAR Base Specification, manages partnership acquisition mechanisms (Data Collaboration Announcement), sets quality levels and ingests datasets from federal, state, and local partners and private contractors, to create a consistent national elevation portfolio.

The 3-D elevation programme, primarily run by USGS, had a total expenditure for FY2024 of \$118.9 million, with USGS NGP (National Geospatial Programme) contributing \$17.3 million towards data acquisition, and \$21 million for programme management and data, validation, processing and delivery (USGS, 2024). The vast majority of funding was provided by partners for data acquisition totalling \$69 million. For FY2025, a fund of \$23 million, from the Inflation Reduction Act (IRA) was put towards 3DEP, 70% of this was used towards data acquisition and to local, state, federal and other partners for the programme (USGS, 2025b). Additionally, the next generation of 3DEP budget is projected to increase to \$259 million annually, depending on the quality level implemented (Lukas et al., 2025). Acquisitions are implemented through partnerships and an open proposal process (Jones et al., 2024; Harrington and Walters, 2025; Cretini, 2025). This results in a patchwork of partnerships (Figure 4) rather than a single federal-only procurement. All products are freely available without use restrictions (USGS, 2025d), supporting applications in hazard mitigation, transport planning, ecological monitoring, and hydrography for flood management (Rowan, 2025).

The USGS manages 3DEP, providing nationwide LiDAR coverage at 0.5– 8 pts/m² (USGS, 2025c), and by FY 2024, 98.3% of the United States was aimed to be surveyed (Lukas et al., 2025). Additional programmes of IfSAR collection across Alaska are aimed to provide baseline reference data for future 3-D surveys, providing a standard for quality control (USGS,

2025a). The objective is to have repeat elevation mapping projects, enabling change detection and temporal analysis across the continental USA.

3DEP integrates machine learning workflows (Liu et al., 2024), satellite-derived elevation data, and cloud-native dissemination (Arundel et al., 2015; Lukas and Stoker, 2016). Recent technical developments focus on machine learning enhancements, including transformer-based deep learning for automated point cloud classification (USGS, 2025d). These workflows aimed to reduce errors in noisy or misclassified tiles, thereby improving downstream applications in hydrology, urban planning, and hazard assessment.

3. Discussion

3.1 Organisational Structure and Governance

Based on the literature explored, the analysis of national 3-D programmes reveals diverse financial structures shaped by different "national good" provision theories (summarised in Table 1). These different economic models cannot be readily used to determine the "best" or "optimal" financial structure of a NMCA, these being shaped by the societal and political climates of the host country. This instead highlights the various methodologies or funding approaches used for supplying national scale 3-D geoinformation by incumbent governments to/via NMCAs. France employs a mixed state-regional model through subsidiarity, with baseline infrastructure provided by the national government and enhanced regional coverage. Germany heavily invests in digitalisation, treating 3-D data as national infrastructure, with a three-year update cycle ensuring stability and consistency. Kadaster's model in the Netherlands relies on market-driven public mapping, generating substantial revenue without full state subsidy. Japan's funding focuses on disaster mitigation, emphasizing rapid deployment of 3-D data to minimize emergency response times and economic losses. Additionally, the doubling of Japan's budget from 2023 to 2025 highlights a priority in digitisation of their national mapping database. The US uses a partnership model, with costs distributed across federal, state, and private entities, ensuring widespread coverage. This is emphasised by c. 58% of their expenditure for 3DEP being funded by partners.

These variations underscore that no single model guarantees sustainability. However, evidence suggests that agencies demonstrating tangible societal and economic benefits, from reduced disaster risk to enabling smart cities, are better positioned to secure long-term funding (Coote et al., 2017). The critical factor is not the funding source per se, but rather the institutional capacity to articulate value propositions aligned with national policy priorities. Financial innovation, including subscription services and value-added applications, is likely to play an increasing role in ensuring sustainability moving forwards.

3.2 Quality Assurance and Standards

Quality assurance at petabyte scale differs from traditional cartographic validation, as 2D statistical sampling methods become computationally infeasible for billions of semantically labelled 3-D points. Automated validation frameworks are therefore necessary to detect errors at ingestion rather than through post-processing. France combines AI with human inspection, achieving 98% precision and recall for buildings and vegetation, though performance degrades for under-represented classes. Germany emphasises interoperability via

Agency	Primary Funding Source	Funding	Open Data Policy
IGN (France)	State + Regional partnerships	€57 million (LiDAR HD)	Yes
BKG (Germany)	Federal digitalisation fund	€44.3 million (Digital Twin Germany)	Yes
Kadaster (NL)	75% commercial revenue	€282.6 million (Annual Budget)	Yes (PDOK)
GSI (Japan)	Central Government	¥13.39 billion / ¥4.82 billion	Yes (Public Domain)
USGS (USA)	Federal + partnership co-funding	\$ 118.9 million	Yes (Public Domain)

Table 1. Economic models and funding structures of national 3-D programmes.

CityGML and CityJSON, using federated validation to reveal boundary inconsistencies, prioritising uniform semantic conformity over absolute accuracy. The Netherlands employs community-driven validation through open-source platforms, crowdsourcing error detection with automated re-processing triggered by user reports, although rural areas receive less scrutiny. Japan focuses on error-tolerant systems for disaster applications, prioritising operational robustness over precision and validating performance through simulations. The United States applies risk-based sampling in 3DEP, concentrating validation on high-risk areas while accepting lower density elsewhere, optimising safety-critical accuracy within resource limits. International standards from OGC and ISO support interoperability, while organisations such as EuroSDR promote cross-border harmonisation. Remaining challenges include balancing resolution and accuracy with computational feasibility and updating standards to accommodate emerging data modalities.

All examined NMCAs adopt open data policies, though motivations and implementation differ. USGS and Kadaster treat openness as a legal requirement, while IGN and BKG frame it as an economic stimulus with demonstrated downstream multipliers. Japan positions open access as civic resilience, maintaining priority even under fiscal constraints.

3.3 3-D Topographic Surveys

The majority of the examined 3-D topographic surveys are committed by agencies to put towards development of a digital twin model, such as Germany, Japan or the Netherlands. Although France mentions putting data from LiDAR HD towards digital twin incentives, the main motivation appears to stem from using this as a national benchmark for current and future data collection programmes, though no published plans for future programmes following LiDAR HD’s completion in 2026 could be found at the time of writing. The USGS appears to have no specific objective for digital twin production with 3DEP, however further research could be carried out into state or local agency aims for digital twins considering the geographical coverage of the United States to other case studies explored.

Additionally, the progress towards digital twins is reflected by the point densities provided (summarised in Table 2). France and Germany, both with point densities of 40 pts/m², aim to

have very detailed urban and forestry mapping and 3-D modelling, which would require high resolution to capture small structures and fine vegetation detail. The Netherlands AHN4 targeted large-scale topographic mapping, which with balancing cost and detail, 20-30 pts/m² was considered reasonable. The relatively lower density for the United States and Japan, can be explained by the continental scale for the United States, and sufficient national-scale mapping resolution. Even though these figures have been provided by the NMCA’s, local projects or specific areas may have different point densities.

3.4 Artificial Intelligence and Automation

Examination of the level of AI adoption across NMCAs highlights a spectrum of strategic approaches influenced by operational and governance contexts. A summary of findings is provided in Table 2. France’s Myria3D system exemplifies an AI application in mapping, achieving 96% production automation and shifting human roles towards quality assurance. This approach addresses labour and computational cost bottlenecks in large-scale data processing. Germany focuses on standardised, hybrid AI-rule-based systems to balance regional diversity and achieve interoperable outputs. The Netherlands harnesses open-source and academic collaboration to drive innovation, reducing research and development costs while necessitating strong quality controls. The United States applies AI to expansive datasets using transformer architectures that handle spatial variations, although funding-dependent data collection poses heterogeneity challenges. Japan’s GSI applies recurrent neural networks and multimodal fusion to integrate multiple sensing modalities for infrastructure monitoring and hazard mapping (Uchiyama et al., 2025).

Across these nations, hybrid AI-rule systems are common, aiming to manage data gaps and improve efficiency, suggesting a trend towards more scalable methods.

3.5 Digital Twin Implementation

Development of national digital twins represents the next stage in the utilisation of 3-D data by NMCAs. IGN has aligned the LiDAR HD dataset with its broader ambition to support national digital twin frameworks integrating environmental and infrastructure data. Germany’s Digital Twin Germany, demonstrates how federal coordination can integrate diverse data

Agency	Programme	Point Density (pts/m ²)	Update Cycle (years)
IGN (France)	LiDAR HD	40+	5
BKG (Germany)	Digital Twin	40+	3
Kadaster (NL)	3D BAG	20-30	AHN1-5 length (Variable)
GSI (Japan)	PLATEAU	4	Variable
USGS (USA)	3DEP	0.5–8	Variable

Table 2. Comparative technical specifications of national 3-D mapping programmes.

sources within a consistent national platform. Kadaster’s open-source Netherlands3D and 3DBAG initiatives show how open data and shared tools can enable sector-specific digital twin applications (Netherlands3D, 2024). Japan’s Project PLATEAU supports municipal-scale digital twins focused on disaster resilience and urban management (Seto et al., 2023). In the United States, while there is no single digital twin programme, USGS datasets form a base layer for multiple agency-driven initiatives using elevation and land cover data for analysis and simulation.

Across these examples, the main challenge is not technical feasibility but coordination. Centralised systems achieve uniformity but rely on sustained investment and inter-ministerial cooperation. Federated and open approaches, as seen in Germany and the Netherlands, provide flexibility and innovation but require strong governance to maintain data coherence. Digital twins therefore illustrate how 3-D mapping has evolved from data production to an operational framework that supports national decision-making.

3.6 Summary of Comparative Insights

Despite structural differences, NMCAs face common challenges: sustainable funding, quality assurance, responsible automation, and coordination. Centralised models ensure coherence but require political commitment; federated approaches offer flexibility but demand continuous coordination. Quality control increasingly integrates automation with expert oversight, while digital twins exemplify evolution from data provision to analytical platforms requiring cross-sector governance.

4. Summary

4.1 Convergence and Divergence Across NMCAs

The comparative study reported in this paper reveals both convergence and persistent diversity in NMCA approaches to 3-D geoinformation infrastructure. Convergence is evident in AI

adoption, open data commitments, and digital twin ambitions. Diversity persists in governance structures, funding models, update strategies, and application priorities. Critically, this diversity is not merely transitional, but rather reflects established structural and cultural differences in political systems, territorial characteristics, and societal priorities that will continue to shape distinct national approaches. Key findings have been summarised in Figure 5.

4.2 Limitations and Future Research

This study examines five leading NMCAs with mature 3-D programmes. Rapid technological advancement may supersede current practices through emerging sensors, cloud computing, or AI developments. Economic models remain context-dependent, influenced by land values, regulatory frameworks, and civic engagement patterns that vary across jurisdictions. Future research should track NMCA evolution over decades, examine developing country contexts with differing resource constraints and governance capacities, and quantify economic impacts through rigorous methodologies isolating 3-D data contributions from correlated factors.

4.3 Conclusion

The transformation of NMCAs from 2-D map producers to 3-D infrastructure and solution providers tracks the evolution in geospatial scientific research. This study demonstrates that governance structures, funding sustainability, quality assurance frameworks, and demonstrated societal value translate into productive modern NMCAs. The five organisations studied collectively illustrate multiple viable pathways rather than a single optimal model. France’s centralised innovation, Germany’s federated coordination, the Netherlands’ market-oriented approach, Japan’s disaster-focused prioritisation, and the United States partnership-based continental coverage. Each succeeds within their respective contexts whilst also facing distinct challenges. International cooperation can accelerate progress through shared learning, but naive transfer of models

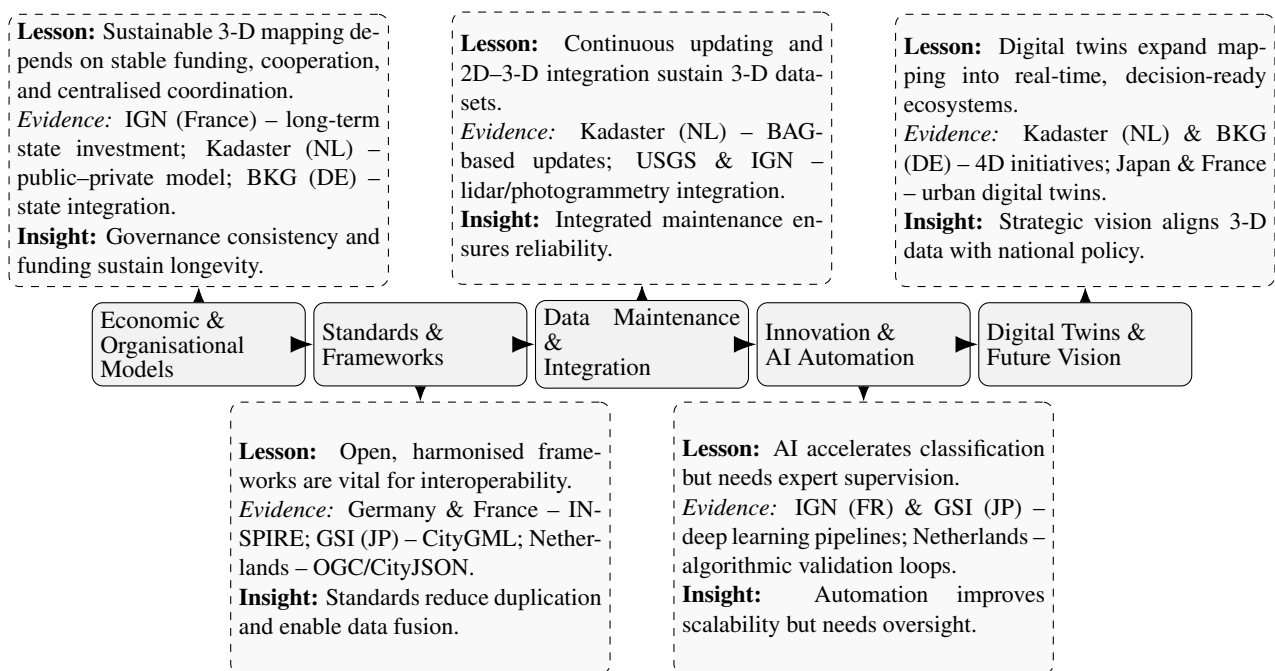


Figure 5. Flow of NMCA 3-D development stages and associated lessons. Dashed lines indicate lessons, case study evidence, and derived insights contributing to sustainable, interoperable, and automated 3-D mapping practices.

across contexts risks failure when structural prerequisites are absent. Furthermore, although each NMCA has unique but similar methods for collecting, processing, and disseminating 3-D data, this study highlights the overall importance and value of national 3-D geospatial datasets.

By synthesising strategies across diverse governance and funding contexts, this paper provides evidence-based guidance for agencies at all stages of 3-D programme development. The convergence of technical approaches alongside persistent governance diversity suggests that future progress depends less on technological breakthroughs than on institutional innovation: developing governance frameworks, funding mechanisms, and international cooperation structures that match the technical capabilities already demonstrated by leading national scale programmes.

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