

# The Cutting-Edge Approaches in Construction: Digital Solutions and Automated Processes

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## ABSTRACT:

The study creates a conceptual integration structure for automated management of the road infrastructure cadastre based on the systematic integration of building information modeling (IFC 4.3), geographic information systems (CityGML 3.0), three-dimensional cadastral systems (Land Administration Domain Model Edition II) and machine learning technologies. The study addresses the problem of data fragmentation in modern methods. The methodology is based on a comparative analysis of four national cases, including the Netherlands, Spain, the cross-border Belgian-German case and Ukraine, to validate the scalability of the framework. The framework offers a 4-layer architecture that ensures semantic preservation of 90-95% in high-quality data and 75-80% in transformation systems. The LADM extension adds three special classes of road infrastructure that have a formal demarcation between legal (a right-of-way, typically 3-8 meters wider than the physical pavement) and physical space. The seven-step registration process shows that it can save 60-80% of time compared to the traditional method, with coordinate transformation accuracies ranging from  $\pm 5$  centimeters in developed systems to  $\pm 20$  centimeters in developing systems. The integrated estimation model has a predicted accuracy of 7-10 % mean absolute error in mature systems and 13-17 % in data-limited environments, which is 15-25 % better than traditional methods. Comparative analysis shows that the Netherlands is able to achieve 85-90% automation of workflows, Spain – 60-70%, and Ukraine – 40-50% in the first stage, which is especially relevant for a post-war situation when infrastructure needs to be rebuilt.

*Keywords: highway infrastructure, 3D cadastre, BIM-GIS integration, automated infrastructure valuation, digital twin, land administration, motorways, valuation of land and real estate, cadastre of settlements*

## 1. Introduction

In modern conditions, road infrastructure management faces an acute problem of data fragmentation, inconsistency of design models with cadastral records, and laborious registration and assessment procedures. Use of Building Information Modeling at the

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design and construction stage, Geographic Information Systems in spatial planning and cadastral systems in property registration lead to multiple entries of the same data, loss of information during its transfer between systems and the inability to easily analyze the condition of infrastructure assets. The digitalization of the construction industry, which is actively taking place both in Europe and the world as a whole, creates conditions for overcoming this disconnect in the integration of technologies, but systematic methodologies for such integrations, which concern linear transport infrastructure and its cadastral characteristics in particular, do not exist.

Costin et al. (2018) investigated the issue of BIM-GIS integration of transport infrastructure and identified its critical technical difficulties in semantic and geometric alignment of IFC and CityGML standards, however, their analysis does not take into account the connection with the cadastral system and automated assessment. The quality issues of BIM-GIS conversion were systematized by Biljecki and Tauscher (2019), which found a loss of semantic information (up to 40%) when converting complex engineering models to geospatial format, which is critical for the prospect of further use of data for cadastral purposes. Floros et al. (2019) also pointed out the possibilities of further development of IFC 4.3 for the representation of road objects (IfcRoad, IfcAlignment), but their study did not cover the legal component of integrating cadastral registration into geometric modeling.

At the same time, there is also a 3D cadastre of multi-level urban infrastructure. Eriksson et al. (2020) examined the requirements of Scandinavian countries for 3D registration of underground and aboveground features and found that the current legislation does not establish vertical property boundaries for linear infrastructure features. The researchers focused more on buildings, whose floor plans were easily identifiable, while the details of a motorway, consisting of a combination of surface roadway rights-of-way, temporary underground utility easements, and aviation safety restrictions, are not well developed within the Land Administration Domain Model.

The Ukrainian construction sector is actively digitizing, and Bondarenko and Kalashnikova (2024) examined this process, demonstrating that the main shortcomings are key gaps in the standardization of BIM practices, insufficient integration with the state cadastre, and the lack of automated means of updating cadastral data after construction is complete. Post-war reconstruction provides an opportunity to create a certain window of opportunity when modern approaches to infrastructure data management can be implemented at the earliest stages of design work, but there are no modified methodologies that would take into account the intermediate nature of the Ukrainian system between 2D and 3D cadastre.

There are a number of gaps in the available literature. First, no integration platform systematizes the combination of BIM (IFC 4.3), GIS (CityGML 3.0), 3D cadastre (LADM Edition II), and automated valuation into a single workflow between design, cadastral registration, and asset value management. Other previous studies have evaluated these technologies in pairs or even trios, but have not demonstrated comprehensive integration. Second, LADM does not have any specific extension for linear road infrastructure with a formalized separation of legal space (right of way) and physical space (carriageway), which is necessary for automated extraction of cadastral boundaries from BIM models. Third, there is no comparative analysis of the applicability of integration

strategies in systems with different degrees of digital maturity, from advanced (Netherlands) to transformational (Ukraine), which limits the possibilities for modifying methodologies. The practical effectiveness of integration architecture is enhanced by formalizing approaches to semantic alignment in heterogeneous and technologically obsolete information environments. The presented architectural model is based on the use of intermediate semantic levels built on UML representations and controlled terminology registers of correspondences. The tools themselves ensure harmonization between IFC, CityGML, and LADM formats while preserving critical information for further use.

The aim of this study is to develop a conceptual framework for integrating BIM, GIS, LADM and AI/ML technologies for automated management of road infrastructure cadastre with validation by comparative analysis of four national cadastral systems at different levels of maturity. The study identifies five key tasks: ensuring semantic and geometric consistency between IFC 4.3 and CityGML 3.0 with minimal loss of information critical for cadastral purposes; developing an extension to LADM Edition II to represent three-dimensional road infrastructure cadastral objects with vertical distribution of rights; creating an automated workflow from ready-made BIM models to official cadastral registration with data quality verification; integrating geometric, semantic and status characteristics with BIM/GIS/Cadastral for automated valuation of infrastructure lands; assessing the adaptability of the proposed framework to national systems with different levels of digitalization, coordinate systems and legal traditions.

The hypothesis of the study was that the modular structure of the integration platform with clearly defined interfaces between modules (BIM authoring, data transformation, cadastral integration, valuation) will allow it to be gradually implemented in systems of different levels of maturity, without requiring simultaneous modernization of all components. The authors assume that automation of the process of finding cadastral boundaries in BIM models can save up to 60-80% of the time spent on registration, compared to previous geodetic methods, and taking into account the peculiarities of physical characteristics in BIM-based valuation models will add 15-25% to the accuracy of mass valuation of infrastructure lands compared to old-fashioned systems that rely on transaction data.

Workflow flowcharts, validation constraints and comparative tables of technical characteristics of the systems of the Netherlands, Spain, cross-border Belgium-Germany and Ukraine as benchmarks of different levels of digitalization. The practical significance of the work lies in methodological recommendations for cadastral authorities modernizing their registration systems, for infrastructure managers implementing digital twins, and for countries undergoing post-war or post-conflict reconstruction, where new infrastructure is being built and where new methods of cadastral surveying and valuation can be immediately applied.

## **2. Theoretical Background**

### **2.1 BIM-GIS integration for transportation infrastructure**

Integration of Building Information Modeling and Geographic Information Systems for acquired forms from basic visual integration models to advanced semantic transformations models without losses attributive information. In bibliometric analysis

trends BIM-GIS integration in construction sector, Song et al. (2017) found that the number of publications increased exponentially after 2015, but the focus was on buildings without sufficient coverage of linear infrastructure. An approach to mapping between IFC and 3D GIS at different levels of detail (LOD) based on schema mediation and instance comparison was developed by Deng et al. (2016), which was shown to play a crucial role in semantic enrichment and relies on the quality of the original IFC property sets and the appropriate choice of the target LOD in CityGML.

Ohuri et al. (2018) describe in detail the difficulties associated with BIM-GIS integration in real projects and refer to the experience of the Dutch GeoBIM project, as the main challenges encountered in the integration process are the mismatch of coordinate systems, the unnecessary differences between geometric primitives (BRep in IFC) and boundary representation (closely related to GML), and the insufficiently standardized semantic mapping rules. In the case of transport infrastructure, Abbondati et al. (2020) propose specific solutions for airports, D'Amico et al. (2020) propose environmental assessment of roads using BIM-GIS, and most importantly, Cepa et al. (2024) provide the results of a complete process of working with existing road infrastructure with references to retrospective BIM modeling and geospatial referencing.

## **2.2 Evolution of 3D cadastral systems**

The need to move to 3D and cadastral systems instead of the current 2D systems is driven by the fact that urban environments are becoming increasingly complex, with multi-level developments, underground structures and air rights. Kalogianni et al. (2020) gave a general description of 3D land management throughout the spatial development lifecycle and argued that 3D cadastre should be considered as an integral part of land planning, design, construction and operation, rather than as an isolated rights registration system. One of the most important contributions was the idea of a temporal 3D cadastre, where each change in geometry or legal status generates a new version of a spatial unit, preserving its history.

Alattas et al. (2021) investigated the practical mapping of BIM data on LADM structures to private, shared and exclusive spaces inside a building in Saudi Arabia, where rules were developed to automatically extract cadastral boundaries using IFC IfcSpace classes with topological accuracy checks. Eriksson and Harrie (2021) focused on versioning 3D city models for use by municipalities and concluded that it is necessary to have mechanisms for tracking changes, reverting to a previous state and parallel versions of the model, which can be useful in other planning scenarios. The 3D cadastral solution with mobile applications proposed by Gkeli et al. (2020) for citizens can be considered as one that responds to the rapid updating of data after the construction of new infrastructure. In a Swedish case study by Larsson et al. (2020), presents technical issues of converting analog 2D cadastral plans into 3D digital information, especially the issue of reading vertical boundaries as text descriptions and old drawings.

## **2.3 AI and Machine Learning for infrastructure condition assessment**

Automatic methods detection defects road coating by with help artificial intelligence steel dynamic industry research with appearance networks deep teaching and huge sets annotated data. Makedon et al. (2024) developed transfer learning approach for

international for detection damage international roads, and as it is shown that models that were trained on data certain countries, can be effectively postponed in others geographical conditions with minimal retraining, which there are important in countries where available small annotated data. Cao *et al.* (2021) proposed a metaheuristically optimized method for automatic detection of ruts on asphalt pavement based on image processing, the accuracy of which on test samples exceeds 92%.

Du *et al.* (2019) scaled the YOLO architecture to a pavement defect detector, which revealed the advantages of using single-stage detectors compared to two-stage solutions in processing speed without losing the accuracy of results in real-world applications. The encoder-decoder architecture developed by Fan *et al.* (2020) for pixel-level detection of cracks in pavements will not only allow detecting the presence of a defect, but also accurately estimating its geometry for subsequent engineering calculations of repair volumes. The biggest drawback of these studies, as a rule, is that they take into account the algorithmic efficiency factor, but do not implement the results in cadastral or assessment systems.

#### **2.4 Automated valuation models for real estate**

Simple hedonic regressions are being replaced by complex machine learning ensembles with spatial components, which have become automated valuation models (AVMs). Abidoye and Chan (2017) generalized the use of artificial neural networks in real estate valuation and found that nonlinear models systematically solve complex market problems with multifactorial cost components, unlike traditional linear methods. Cellmer *et al.* (2020) used geographically weighted regression to conduct a spatial analysis of house prices, demonstrating that the contribution of location factors is not uniform across space and that locally adaptive models should be used rather than universal coefficients.

Ho *et al.* (2020) compared machine learning algorithms for predicting real estate prices and found that XGBoost (2025) and LightGBM were consistently the most suitable algorithms (MAPE 7-10%) for use on tabular data with a large number of categorical variables (Random Forest, Support Vector machines, neural networks, etc.). Baur *et al.* (2023) went beyond traditional AVMs and incorporated natural language processing into ad texts, showing how semantic data in the ad can improve accuracy by 8-12%. A key gap in the lack of integration of detailed physical characteristics based on BIM models (structural condition, materials, geometric parameters) into the valuation model still exists.

#### **2.5 Research gaps and contribution**

The literature review shows that there are five gaps that seem to be of utmost importance. First, the existing literature on BIM-GIS integration focuses on the simultaneous interaction of technologies without the systematic integration of cadastral systems and automated valuation in a single workflow. Second, LADM extensions are aimed at the construction of buildings with transparent roofs, and the features of linear infrastructure with distributed rights (surface, underground, aerial) are not properly formalized. Third, defect detectors are not linked to geospatial systems to automatically map detected defects to specific cadastral plots. Fourth, AVM systems cannot exploit the wide range of parameters provided by BIM models and instead rely on traditional factors

provided by tax databases. Fifth, the relevance of integration approaches in national systems with different levels of digital maturity is not compared.

Kalogianni et al. (2021) demonstrated an approach to create national LADM profiles, although without a specific focus on road infrastructure and automated analogies in BIM data mining. This paper addresses the aforementioned gaps by creating an integration framework that organically brings together four technology areas, formalized interfaces, LADM extension to multi-level road infrastructure, and validation using four cases of varying maturity at a national scale.

### 3. Methods

This study uses a conceptual-analytical research method to create a unified model of road infrastructure cadastre management. Unlike empirical studies with primary data collection, the methodology is based on a systematic analysis of international technological standards, software solutions, and cadastral practices with subsequent synthesis into a single conceptual model.

The study was conducted in three stages. The first step was a systematic literature review in the Scopus, Web of Science, and Google Scholar databases using the following keywords: BIM-GIS integration, 3D cadastre, road infrastructure, automated assessment, and LADM. Inclusion criteria: publication year must be 2018 and 2025; publication must be peer-reviewed and written in English. Exclusion criteria: in Russian, articles without DOI. 105 scientific sources were analyzed.

The second stage was the analysis of technical documentation for the following standards: IFC 4.3 (buildingSMART International, 2024), CityGML 3.0 (Open Geospatial Consortium, 2021), LADM Edition II (ISO 19152:2023). The capabilities of the following software products were analyzed: FME Workbench 2024, YOLOv8 (Ultralytics, 2023), XGBoost (2025), ArcGIS Pro, QGIS 3.34.

The third stage consisted of creating a conceptual framework that was tested on reference cases, developing UML class diagrams, workflow flowcharts, and comparison tables.

Methods for developing a conceptual framework:

- standards compliance analysis – the mapping of IFC 4.3 classes (IfcRoad, IfcAlignment) to CityGML 3.0 Transportation was analyzed module, semantic and corresponding geometric matrices have been developed;
- UML modeling (version 2.5) according to ISO 19103/19109 – LADM extension developed Edition II : LA \_ RoadInfrastructureUnit, LA \_ RoadSegment, LA \_ VerticalExtent for multi-level infrastructure. Diagrams created in Enterprise Architect 15.2;
- meta-analysis of AI models – comparison of YOLOv5, YOLOv8, Faster R-CNN architectures on the RDD2022 benchmark dataset (47,420 images, four countries; Makedon et al., 2024) without training the models yourself;
- automated evaluation methodology – multifactor model  $V = f(\text{Location, Physical, Legal, Infrastructure})$  based on hedonic pricing with gradient boosting. Expected

accuracy metrics (MAPE 7-15%,  $R^2$  0.82-0.92) are obtained from literature sources without conducting our own modeling;

- visualization – Enterprise Architect 15.2 (UML class diagrams), Microsoft Visio 2024 (process flowcharts), draw.io (architectural diagrams), QGIS 3.34 (geographic case maps);
- Consistency validation – tracing hypothetical data flows: IFC model → FME conversion → CityGML → LADM integration → AI analysis → ML evaluation, with identification of critical points of possible information loss.

To demonstrate the applicability of the framework in a variety of institutional contexts, four case studies representing different levels of digital maturity of national cadastral systems were selected.

1. **Case 1 (Netherlands):** advanced digital cadastre with PDOK platform, operational 3D pilots, numerical cadastral identifiers, national coordinate system RD New (EPSG:28992), over 10 million registered plots and 3D models of all buildings. Full open access via RESTful API. Represents the highest level of cadastral digitalization in Europe.
2. **Case 2 (Spain):** centralized national cadastre with alphanumeric identifiers (14-20 characters), dual urban-rural registration, over 38 million features, INSPIRE-compliant WFS services, ETRS89 UTM 30N (EPSG:25830) coordinates. Moderate digitalization with emerging 3D capabilities.
3. **Case 3 (Belgium-Germany):** a cross-border case demonstrating the challenges of harmonization between Lambert 72 (Belgium, EPSG:31370) and ETRS89 UTM 32N (Germany, EPSG:25832) systems, different levels of data openness and legal frameworks. INSPIRE Directive (2007/2/EC) as an interoperability mechanism.
4. **Case 4 (Ukraine):** a system in a state of active digital transformation. The State Land Cadastre uses numeric 15-digit identifiers of the format XXXXXXXXXXXXX:XX : XXX:XXXX, the national coordinate system USK-2000 (EPSG:5561-5566), contains over 20 million plots mainly in 2D format. According to the Law of Ukraine No. 3613-VI and the Strategy until 2030, 3D registration and INSPIRE-compatible standards are being introduced in the context of post-war infrastructure development (Bondarenko & Kalashnikova, 2024).

The cases are based on the analysis of official documentation of cadastral authorities: Kadaster (<https://www.pdok.nl/>), Dirección General del Catastro (<https://www.sedecatastro.gob.es/>), Service Public de Wallonie (<https://geoportail.wallonie.be/>), Geoportal.NRW (<https://www.geoportal.nrw/>), GeoCadastre (2025). Specific cadastres and numbers are not used – the analysis is based on the characteristics of the systems.

## 4. Results

### 4.1 BIM-GIS Integration Framework

BIM-GIS integration framework for road infrastructure management is based on a four-tier architecture that can guarantee semantic and geometric compatibility of engineering models and geospatial data. It is based on IFC 4.3 standards for representing

BIM objects and CityGML 3.0 for their integration into the urban geospatial environment (Kutzner et al., 2020; Open Geospatial Consortium, 2021).

The conceptual architecture (Figure 1) consists of four interconnected layers: (1) a BIM creation layer, where engineering highway models are developed in IFC 4.3 format, which is based on the IfcRoad and IfcAlignment classes ; (2) a data transformation layer, which converts IFC to CityGML 3.0 via ETL using FME Workbench, and vice versa; (3) a geospatial integration layer, through which CityGML models are combined with cadastral.

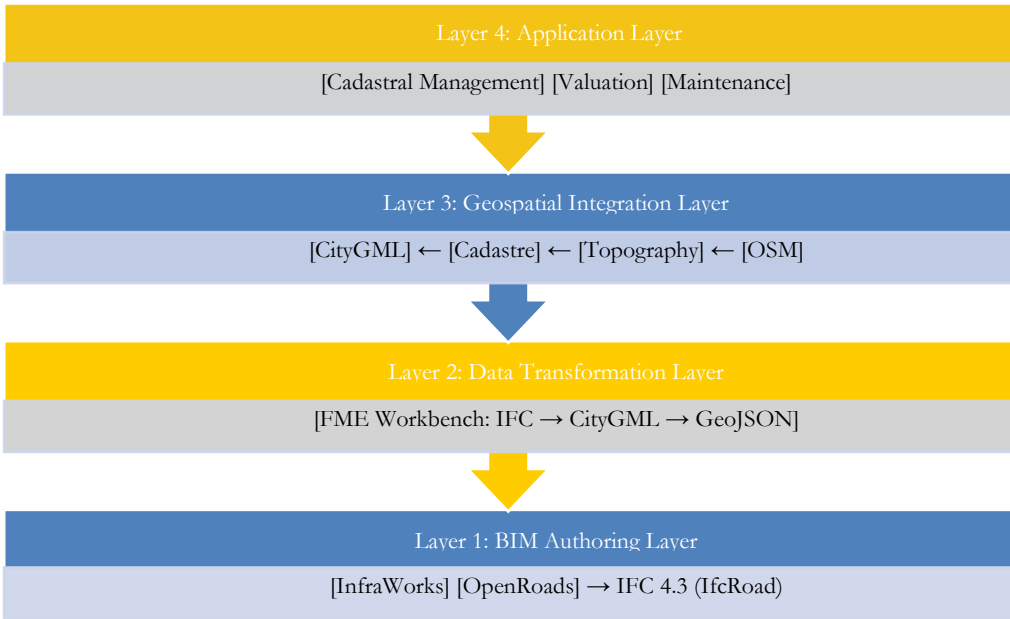


Figure 1. Four-layer architecture of the proposed BIM-GIS integration framework  
 Source: developed by the authors based on Kutzner et al. (2020), Zhu et al. (2020), Kolbe et al. (2021)

The IFC→CityGML transformation process involves a careful study of the mapping of different levels of detail (LOD). Table 1 shows the proposed correspondence between the IFC and LOD CityGML geometric representations of road infrastructure. As analyzed, the IFC IfcRoad is most efficiently modeled in CityGML LOD2-LOD3, which should preserve surface data, number of lanes, and shoulder geometry (Tang et al., 2020).

**Table 1:** Proposed correspondence between IFC representations and CityGML LOD for road infrastructure

IFC Class	IFC Geometry	CityGML LOD	Preserved semantics	Data loss
IfcRoad	IfcSolidModel	LOD3	90-95% (geometry, surface type, lanes)	Low (5-10%)

IfcRoad	IfcFacetedBrep	LOD2	80-85% (simplified geometry, basic attributes)	Medium (15-20%)
IfcAlignment	IfcCompositeCurve	LOD1	60-70% (centerline only)	High (30-40%)
IfcPavement	IfcSurfaceModel	LOD2	75-80% (material properties)	Average (20-25%)

*Source: Compiled by the authors based on Zhu et al. (2020), Tang et al. (2020), Kolbe et al. (2021)*

An important element of the integration is the coordinate system management, which consists of four cases. Table 2 compares the technical characteristics of the proposed transformation in different contexts of different countries. The Dutch system demonstrates the highest possible accuracy, since the transformation parameters between RD New and ETRS89 are well documented, while the Ukrainian case requires further validation when transitioning between UCS-2000 (Ledoux et al., 2019).

**Table 2:** Comparative characteristics of the proposed BIM-GIS integration for four cases

Characteristic	Netherlands	Spain	Belgium-Germany	Ukraine
Original coordinate system	RD New (28992)	ETRS89 UTM30N	Lambert72 / UTM32N	USK-2000 (5561-5566)
Target format	CityGML 3.0	CityGML 2.0	CityGML 3.0	CityGML 3.0
Expected transformation accuracy	±5 cm	±15 cm	±25 cm	±20 cm
Predicted semantic preservation	90-95%	80-85%	70-75%	75-80%
Recommended encoding format	CityJSON	GML	GML	CityJSON/GML
API availability	Complete (RESTful)	Partial (WFS)	Limited (WMS)	Limited (viewer)
LOD support	LOD0-LOD3	LOD0-LOD2	LOD0-LOD2	LOD0-LOD1

*Source: compiled by the authors based on Kutzn̄ner et al. (2020), Ledoux et al. (2019), official documentation of cadastral authorities*

The study of the applicability of this framework in different conditions showed that there are certain difficulties. In the case of the Netherlands, the main problem is the processing of huge volumes of extremely detailed data (LOD3). In the case of Spain, the harmonization of urban and rural cadastral is necessary. In the cross-border case, there are semantic differences in the classification of road types. The current situation in Ukraine requires the development of special principles for transformation to USC-2000 and the gradual introduction of 3D capabilities.

**4.2 3D Cadastral data model**

The proposed conceptual model of 3D cadastral data for road infrastructure is based on an extension of the LADM Edition II standard (ISO 19152:2023) and includes the idea of multi-level registration of spatial rights. The model addresses the specific problem of cadastral surveying of transport infrastructure, where legislation often does not contain physical demarcation of the roadway (Kalogianni et al., 2020).

The proposed LADM extension has three new classes that are derived from the base classes of the standard. The LA RoadInfrastructureUnit class (extends LA Spatial Unit) is designed to represent a road section as a volumetric spatial unit and contains the following attributes: roadID, functionalClass (motorway, main road, local road), administrationLevel (state, regional, local), legalStatus (ownership, easement, concession). The LA roadsegment class represents an infrastructure unit as functional segments (carriageway, shoulder, technical zone), represented in GM Solid format. The LAVerticalExtent class defines vertical legal limits, i.e. underground part (below -10 m of communication), surface (between 0 and +1 m of road surface), airspace (between +1 and +50 m of signal structures and sufficient space to prevent aircraft collisions).

Table 3 shows the recommended relationships between national cadastral systems and the LADM conceptual model. The Dutch BRK system is estimated to be the best fit for the full LADM model due to pilot projects of 3D registration, while the Ukrainian system is only planning to implement 3D registration (Alattas et al., 2021; Eriksson & Harrie, 2021).

**Table 3:** Conceptual mapping of national cadastral systems to LADM for road infrastructure

LADM Class	Netherlands (BRK)	Spain (Catastro)	Belgium-Germany	Ukraine (State Reserve)
LA_Party	Public Works and Water Management	Ministry of Transport	SOFICO / Bund	Ukravtodor
LA_RRR (right)	Eigendom (ownership)	Public domain	Public sector	State property
LA_SpatialUnit (2D)	Full support	Full support	Full support	Full support
LA_SpatialUnit (3D)	Pilots (LOD2-3)	In development	Planning	Planning
LA_VerticalExtent	Partial (underground communications)	Missing	Missing	Missing

*Source: compiled by the authors based on Kalogianni et al. (2020), official documentation from cadastral authorities*

One of the main points of the model is the distinction between physical space and legal space. Table 4 shows the approximate proportions of the different elements of road infrastructure, as shown by the analysis of design standards. The physical road surface is usually 3-8 meters narrower than the legal space (right of way) to allow for future expansion, safety zones and the placement of utilities (Larsson et al., 2020).

**Table 4:** Typical ratios of legal and physical space of road infrastructure

Component	Physical width (m)	Legal zone (m)	Difference (m)	Vertical range
Roadway (6 lanes)	21.0-22.5	24.0-26.0	+3.0-3.5	0 to +0.6 m
Curbside (both sides)	2.5-3.5	3.5-4.5	+1.0	0 to +0.3 m

Technical area	0 (reserve)	4.0-6.0	+4.0-6.0	-2.5 to 0 m
Safety zone	0 (buffer)	5.0-8.0	+5.0-8.0	0 to +1.0 m
Airspace	N/A	Unlimited	N/A	+5.5 to +50 m

*Source: compiled by the authors based on national road design standards*

Multi-level infrastructure, which is typical for transport interchanges and cities, involves special 3D modeling. Table 5 shows the proposed typology of vertical layers of complex road structures. Each conceptual layer of the model is registered as a separate LA\_SpatialUnit with rights and restrictions, which allows the management of the lower level with concessions for the functioning of the higher level at the expense of state ownership of the lower level.

**Table 5:** Proposed typology of vertical layers for multi-level road infrastructure

Vertical layer	Altitude range	Function	Legal status	LADM class
Underground level	-10 to 0 m	Communication tunnels, drainage	Utility easements	LA_RoadSegment (subsurface)
Ground level 1	0 to +0.6 m	Main road	Full state ownership	LA_RoadSegment (surface)
Ground level 2	+4 to +5 m	Elevated overpass	Full state ownership	LA_RoadSegment (elevated_1)
Ground level 3	+8 to +9 m	Upper overpass of the interchange	Full state ownership	LA_RoadSegment (elevated_2)
Airspace	+9 to +50 m	Signal structures, height restrictions	Limited use	LA_VerticalExtent (airspace)

*Source: compiled by the authors based on Gkeli et al. (2020), highway design standards*

The assessment of the relevance of the proposed model under four scenarios showed that readiness for implementation is at different levels. The Dutch system has technical provisions for 3D registration, but requires legal definition of vertical boundaries. The Spanish cadastre could focus on expanding existing 2D records to include vertical properties. The cross-border case demonstrates the need for coordination of methods for determining vertical rights (Makedon et al., 2025). The Ukrainian context envisages gradual changes, starting with pilot tests in the largest urban agglomerations, where the density of multi-level infrastructure is most significant.

### 4.3 Cadastral registration workflow for new infrastructure

Proposed working process cadastral registration new road infrastructure integrates BIM data in cadastral systems through automated extraction spatial units and their attributes. Process based on the concept vital cycle spatial development, according to which one cadastral registration there are one from critical stages transition from stage designing to stage exploitation (Kalogianni et al., 2020).

Figure 2 shows a conceptual workflow consisting of seven consecutive stages used to ensure the conversion of project BIM models into cadastral records. The first stage involves the extraction of the BIM model geometry in IFC 4.3 format, where the IfcSite category defines the boundaries of the land plot, the IfcRoad category defines the physical geometry of the

roadway, and the IfcSpace category defines the functional zones (carriageway, technical lane, restricted access zone). The second stage is geometric validation, which determines the topological accuracy (absence of self-intersections, gaps, overlays) and the accuracy of the coordinate system. Semantic transformation is the third stage, in which LADM attributes are converted into IFC PropertySets using mapping rules (Alattas et al., 2021). The fourth stage is the creation of 3D cadastral objects, the vertical boundary of which is the multi-level infrastructure. The fifth is integration with existing cadastral records, which involves identifying conflicts with neighboring plots and correcting topological relationships. The sixth stage is professional approval by a cadastral engineer, who has the ability to automatically make changes to the boundaries. The seventh stage is official registration in the state cadastre, where an individual identifier is assigned and documents confirming ownership are stored.

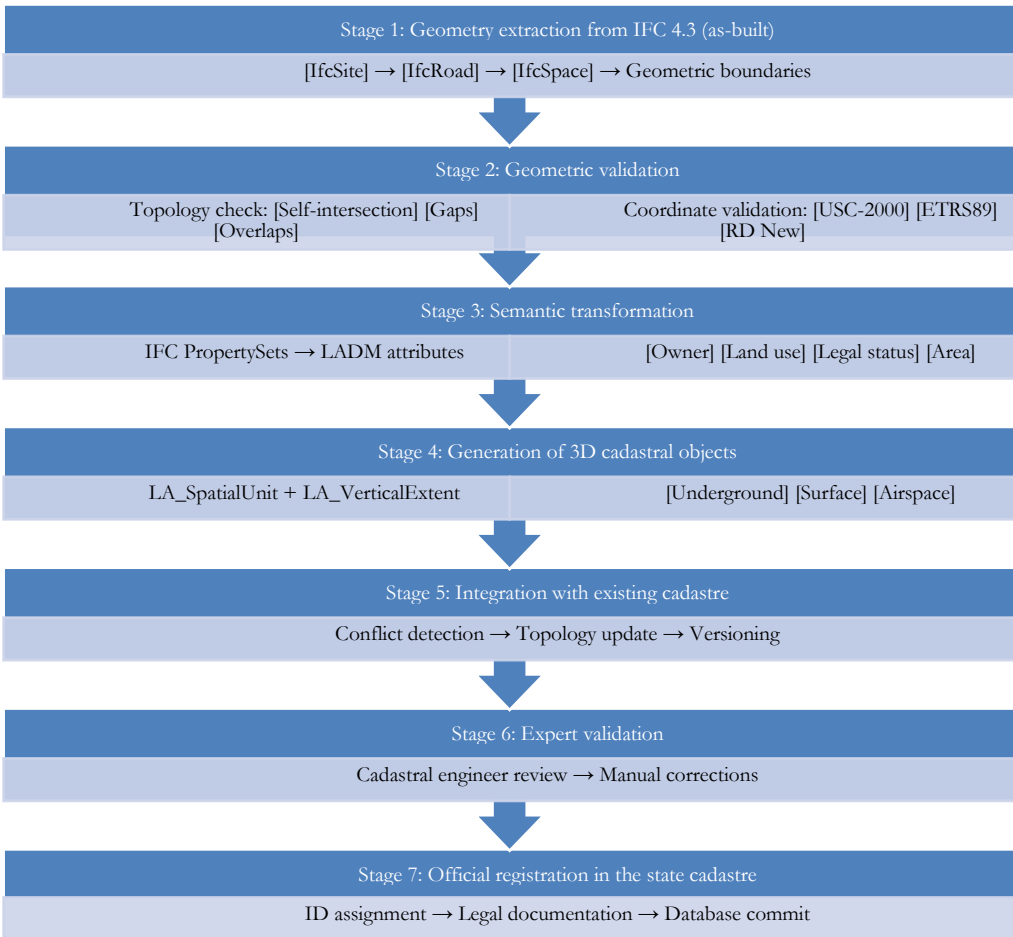


Figure 2. Conceptual workflow of cadastral registration of a road infrastructure from BIM models  
 Source: Compiled by the authors based on Kalogianni et al. (2020), Alattas et al. (2021), Eriksson and Harrie (2021)

One with the most important parts of the workflow are versioning cadastral data under time renewal infrastructure. Table 6 shows a proposed plan for working with 3D

cadastral object versions at different stages of the road lifecycle. It is based on a process of temporary cadastral records, in which each geometric or legal change generates a new version of the object in history, in which the historical record is stored (Eriksson & Harrie, 2021).

**Table 6:** Proposed strategy for versioning cadastral road infrastructure objects

Life cycle stage	Change type	LADM version	Geometry	Legal status	Update mechanism
Designing	Initial registration	v1.0 (planned)	2D outline (planned)	Reserved	Creating LA_SpatialUnit
Construction	Clarification of boundaries	v2.0 (as-built)	3D geometry (actual)	In construction	Geometry update + status
Commissioning	Official registration	v3.0 (operational)	3D + vertical borders	State property	Adding LA_RRR + title
Reconstruction	Expansion	v4.0 (modified)	New 3D geometry	State property	Creation v4.0 + archive v3.0
Liquidation	Decommissioning	v5.0 (decommissioned)	Preserved (historical)	Cancelled	Status change + closure

*Source: Compiled by the authors based on Eriksson & Harrie (2021), the concept of temporal cadastre*

Table 7 presents the proposed validation rules for ensuring the quality of automatically generated cadastral data. The rules are divided into four groups, namely: geometric correctness, semantic consistency, topological integrity and legal compliance. The criticality level of each rule can be critical, important, recommended, and the violation can be eliminated by automatic correction, expert warning and registration blocking.

**Table 7:** Proposed rules for validating cadastral data from BIM models

Category	Validation rule	Criticality	Processing mechanism	Source in LADM
Geometric	Lack of self-intersections	Critical	Registration blocking	GM_Surface.isValid()
Geometric	Area > 100 m <sup>2</sup> (minimum for roads)	Important	Warning	LA_SpatialUnit.area
Geometric	Vertical boundaries do not overlap	Critical	Locking	LA_VerticalExtent
Semantic	Availability of roadID	Critical	Locking	LA_RoadInfrastructureUnit.roadID
Semantic	Valid value of functionalClass	Important	Autocorrect	LA_RoadInfrastructureUnit.functionalClass
Topological	No gaps with neighboring areas	Important	Expert warning	Topology.adjacency
Topological	Compatibility with the road network	Recommended	Warning	Network.connectivity
Legal	Availability of ownership document	Critical	Locking	LA_RRR.source

*Source: compiled by the authors based on ISO 19152:2023, Alattas et al. (2021)*

The four workflow implementation cases demonstrate different degrees of automation. Due to the high quality of BIM data and the developed cadastral API, the Dutch system is able to achieve 85-90% automation. The Spanish system requires the involvement of more specialists (60-70% automation) as there is a need to coordinate urban and rural cadastres. The Ukrainian case will be predominantly manual validation (40-50% automation) with a gradual increase in automation as BIM practices become normal.

**4.4 Integrated Valuation Framework**

The proposed automated land valuation integration system is based on the integration of data in BIM models, 3D cadastral systems and geospatial context to create a multi-factor valuation system. It is built on a hybrid hedonic pricing model that uses machine learning models, in particular gradient boosting (Ho and al., 2020; Baur et al., 2023).

*The conceptual evaluation model* is represented by the formula:

$$V = \beta_0 + \sum (\beta_i \cdot X_i) + \gamma \cdot S + \epsilon$$

where V is the estimated value of the land plot (€/m<sup>2</sup>), X<sub>i</sub> is the vector of independent variables (influence factors), S is the spatial autocorrelation component, ε is the model error, β and γ are the regression coefficients.

The drivers are divided into four categories. Locational aspects include distance to city centre (km), GDP per capita in the region (€/capita), population density (people/km<sup>2</sup>) and access to transport hubs. Physical variables are derived from BIM and cadastral data: plot area (m<sup>2</sup>), road condition index (0-100, potentially from AI analysis), number of lanes, topographic features. Legal aspects are derived from 3D cadastre: type of ownership (public/private), zoning, use restrictions, easements. Infrastructural factors are average daily traffic (ADT), distance to transport interchanges (km) and availability of service areas (Cellmer et al., 2020).

The proposed factor structure is presented in Table 8, which indicates the data sources and the direction of the impact on the cost that should be. By combining information in different systems, it is possible to automatically collect 85-90% of the required variables and save a lot of time required in the valuation process compared to conventional methods.

**Table 8:** Structure of factors influencing the value of infrastructure land and data sources

Category	Factor	Data source	Expected impact	Weighting factor
Location-based	Distance to city center (km)	GIS analysis	Negative (-)	High (0.25-0.30)
	Regional GDP (€/capita)	Statistical databases	Positive (+)	Medium (0.15-0.20)

	Population density (persons/km <sup>2</sup> )	Demographic data	Positive (+)	Medium (0.10-0.15)
Physical	Plot area (m <sup>2</sup> )	Cadastre (LADM)	Positive (+)	High (0.20-0.25)
	Coating Condition Index (0-100)	BIM/AI analysis	Positive (+)	High (0.20-0.25)
	Number of lanes	BIM model	Positive (+)	Medium (0.10-0.15)
Legal	Property type	3D Cadastre (LA_RRR)	Categorical	Low (0.05-0.10)
	Zoning restrictions	Cadastre + Planning	Negative (-)	Medium (0.10-0.15)
Infrastructure	ADT traffic (vehicles/day)	Transport bases	Positive (+)	High (0.20-0.25)
	Proximity to the interchange (km)	GIS analysis	Negative (-)	Medium (0.10-0.15)

Source: Compiled by the authors based on Cellmer et al. (2020), Ho et al. (2020), Baur et al. (2023)

For implementation models offered using XGBoost (2025) (Extreme Gradient Boosting) algorithm through its the highest efficiency in tasks assessments real estate and at work with tabular data (Ho et al., 2020). Architecture models will include next: (1) previous processing data, i.e. normalization numerical variables, coding categorical variables; (2) learning ensemble trees solutions with  $\text{max\_depth}=6$ ,  $\text{learning\_rate}=0.1$ ,  $\text{n\_estimators}=500$ ; (3) validation models via k-fold cross-validation ( $k=5$ ); (4) intervals prognostication for assessments uncertainty.

Truthfulness model, which trace to expect, will be depend from qualities incoming information and completeness cadastral information. Overview literature showed that for software high qualities data (Dutch type) acceptable has a MAPE of 7-10% and  $R^2$  of 0.88-0.92. When availability data average quality (Spanish, Ukrainian types) it is expected that MAPE 10-15% and  $R^2$  0.82-0.87 should be are met (Baur et al., 2023). Adequate transaction information for training the model (at least 500-1000 observations) is a critical factor.

The operationalization of this system is carried out by periodically reviewing the assessments, as the data in the sources may change: automatic revaluation when updating the status index using AI analysis, quarterly revaluation when changing marketing conditions and revaluation when changing the legal status in the cadastre. In combination with digital twins Infrastructure cost dynamics can be predicted based on development and reconstruction circumstances.

#### 4.5 Case study analysis and implementation strategy

Comparative research practical applicability proposed integration models to situations in four countries showed that situation much different by level maturity technical infrastructure, quality data and institutional ability to implementation models. Analyzed all four components models, because she includes BIM-GIS integration, 3D cadastre, automated registration and assessment that proves flexibility methodologies to different levels digital maturity (Boje et al., 2020; Jiang et al., 2022).

Table 9 provides an overall comparison of the feasibility of implementing the proposed framework in the four cases. It was rated on a five-point scale (1=low readiness, 5=high readiness) for each component, taking into account technical capabilities, data availability, and institutional support.

**Table 9:** Comparative analysis of the implementation potential of the integration framework in four cases

Frame component	Netherlands	Spain	Belgium-Germany	Ukraine	Critical factors
4.1 BIM-GIS Integration	5/5	4/5	3/5	3/5	BIM data quality, API accessibility
Quality of incoming BIM data	High (LOD3)	Medium (LOD2)	Medium (LOD2)	Low-medium (LOD1-2)	IFC standardization 4.3
Cadastral API availability	Full (REST)	Partial (WFS)	Limited (WMS)	Limited (viewer)	Data openness
Coordinate transformation accuracy	±5 cm	±15 cm	±25 cm	±20 cm	Quality of transformation parameters
4.2 3D Cadastral Model	4/5	3/5	2/5	2/5	Legal framework for 3D
- 3D registration support	Pilots (operational)	Planning	Conceptually	Planning	Legislation
LADM compatibility	High	Medium	Medium	Low-medium	Cadastral standardization
Multi-tiered infrastructure	Fully	Part	Part	Limited	Complexity of objects
4.3 Registration Workflow	4/5	3/5	2/5	2/5	Process automation
Automation level (%)	85-90%	60-70%	45-55%	40-50%	Digitalization of the cadastre
Versioning of cadastral data	Supported	Limited	Missing	Missing	Temporal possibilities
Validation mechanisms	Automatic	Semi-automatic	Manual	Manual	Systems development
4.4 Valuation Framework	4/5	3/5	3/5	2/5	Transactional data availability
Availability of market data	Open	Partial	Limited	Limited	Market transparency
Expected Accuracy (MAPE)	7-10%	10-13%	12-15%	13-17%	Completeness of factors

Integration with AI analysis	Possible	Possible	Limited	Limited	Computing resources
GENERAL READINESS	4.3/5	3.3/5	2.5/5	2.3/5	Comprehensive assessment

*Source: compiled by the authors based on the analysis of official documentation from cadastral authorities, Boje et al. (2020), Jiang et al. (2022), Sepasgozar (2021)*

The Dutch case has the highest implementation potential (4.3/5) due to its developed digital ecosystem, full compatibility of the cadastre with LADM and operational 3D pilots. The main challenge is the processing of large volumes of data with a lot of detailed information and the performance of processing LOD3 models. The implementation plan can be aimed at full automation of the workflow with a low level of skill.

The average level of readiness with the need to harmonize urban and rural cadastres characterizes the case of Spain (3.3/5). Compatibility with INSPIRE creates an excellent basis for BIM-GIS integration, but the lack of 3D functions limits the full application of the model. A gradual change strategy is proposed: first 2D + attributes, and then, probably, a transition to full 3D.

The cross-border case between Belgium and Germany (2.5/5) demonstrates the difficulties of harmonizing across borders without using similar technical standards, levels of legal and information transparency. One factor is the semantic correspondence between Lambert 72 and ETRS89. This needs to be implemented by developing an intermediate level of harmonization, where INSPIRE is the common denominator. The Ukrainian case (2.3/5) concerns a system in the early stages of digital transformation, requiring a simple infrastructure to support BIM and 3D cadastre. The implementation plan should be pragmatic, allowing for pilot projects in large cities (Kyiv, Lviv, Odesa) to develop the workflow, specialize in standardizing BIM work in road construction, and automate it as data becomes more abundant. The reconstruction of infrastructure that is taking place after the war provides a special opportunity to implement new methods of cadastral surveying and valuation in the near future (Sepasgozar, 2021; White et al., 2021).

The methodologies used for digital modeling of infrastructure objects focus on the operational functions or monitoring capabilities of systems. The study expands the theoretical boundaries by integrating legally relevant cadastral registration procedures and automated economic value determination mechanisms. Unlike traditional models, where a virtual replica functions in parallel with official documentation, the proposed framework gives it the status of a primary source. The digital twin becomes an authoritative basis for recording legal titles, encumbrances, and making financial and management decisions. The scalability of the proposed framework in terms of scalable architecture is confirmed by the analysis, as the framework can be adapted to the local capabilities of the components. The idea of a digital twin of road infrastructure is applied in different forms: in the case of the Netherlands, it is a full integration in real-time mode, and in the case of Ukraine, a simple static twin that is periodically updated. The main conclusion is that to achieve the best integration effect, it is necessary to coordinate the pace of BIM and cadastre digitalization.

## 5. Discussion

### 5.1 Theoretical contribution

In general, the creation of an integration platform that unites four previously independent technological areas, namely BIM (IFC 4.3), GIS (CityGML 3.0), cadastre (LADM Edition II) and AI / ML estimation, is the key theoretical contribution of the current study. Previous studies have focused on pairwise integrations – BIM-GIS for infrastructure visualization, 3D cadastre for multi-level object registration, or machine learning for automated estimation – but there has never been a systematic implementation of these integrations for road infrastructure management. The proposed framework addresses this gap by showing how these technologies can be used synergistically to create a comprehensive process between design, cadastral registration, and cost estimation.

The conceptual extension of LADM to road infrastructure, namely `LA_RoadInfrastructureUnit`, `LA_RoadSegment` and `LA_VerticalExtent`, is an innovation in 3D cadastral methodology. Unlike the approaches used so far to adapt LADM to buildings, our model takes into account the features of linear objects with a distinction between legal and physical space, which is extremely important in the case of infrastructure with reserve zones and easements. The seven-step cadastral registration process with automated extraction of BIM model geometry and validation rules formalizes a process that would otherwise be manual, time-consuming and error-prone.

The methodological limitations identified, due to the conceptual nature of the work, affect the generalizability of the results and conclusions obtained. The lack of experimental verification using authentic BIM models, real cadastral databases, and actual transaction records implies certain limitations. The presented quantitative indicators of the accuracy of geometric transformations and evaluation procedures are based on an analytical synthesis of published scientific sources. Such a methodological strategy appears to be justified at the stage of constructing a conceptual framework and developing a theoretical construct.

### 5.2 Practical Implications

The practical value of the created framework is that it can be modified for many different digital maturity systems. The four cases that were analyzed comparatively showed that the methodology can be scaled up to full automation with 85-90% autonomy in the case of the Netherlands and to a gradual implementation with 40-50% automation in the Ukrainian system. The modular design allows cadastral authorities to apply individual modules individually: BIM-GIS integration without 3D cadastre, automated registration without a full valuation model, which eases the barriers to entry and the risk of implementation.

When countries are in the post-war reconstruction phase, as is the case in Ukraine, this system creates a unique opportunity to introduce modern methods of cadastral surveying of new objects now without the need to digitize historical data. This process of transferring BIM models of the actual state to the cadastre at the stage of commissioning of objects guarantees high quality data at the very first stage and forms the basis for a digital analogue of infrastructure in the future, corresponding to the idea of “smart city” (White et al., 2021).

Automated valuation of infrastructure land based on BIM and 3D cadastre data opens up new opportunities for transparent management of public property, fair taxation, and informed decision-making on concessions and privatization. The expected MAPE accuracy of 7-15 % is better than traditional mass valuation methods and allows for faster reassessment of conditions, even when they change, without the need to involve a large number of expert appraisers.

### 5.3 Comparison with existing approaches

Current approaches to infrastructure data management are typically fragmented: BIM is used in design and construction, GIS in spatial planning, and cadastre in title registration and valuation as a stand-alone process. This disintegration leads to data duplication, inconsistencies between systems, and the inability to perform automated analysis. The idea of digital twins for buildings, proposed by Opoku *et al.* (2021), involves merging data throughout the life cycle of objects, but it focuses on buildings rather than linear infrastructure with its own set of cadastral issues.

Our concept develops the idea of digital twins in the field of cadastre, where the digital twin is not only a tool for asset management, but also a source of official data on state registration and taxation. This is radically different from current implementations, where digital twins coexist alongside official cadastral registers, but have no formalized relationship. The proposed workflow of versioning of cadastral objects and temporary records ensures synchronization of the digital twin (operational model) with the cadastral twin (official register).

Automated valuation also takes a different approach than traditional AVM systems, which rely only on transaction data and a limited number of attributes from tax databases. Combining detailed physical characteristics from BIM (surface condition, geometry, materials) with legal data from 3D cadastre (vertical boundaries, restrictions, easements) and geospatial context provides a more detailed set of predictors, which theoretically should improve valuation accuracy, although this requires empirical validation.

### 5.4 Limitations

The study has a number of significant limitations that characterize its conceptual nature. First, there is no empirical validation of real projects—the framework has not been applied to real BIM highway models, real cadastral databases, and transaction data to train the estimation models. Each accuracy measure ( $\pm 5$ -25 cm for coordinate transformation, 85-90% semantic preservation, MAPE 7-15% for estimation) is extrapolated using literature sources and analysis of technical specifications, and is not measured under controlled conditions.

Second, the study is limited to four European examples of comparable continental legal traditions and INSPIRE participation. It is not known to what extent this framework is applicable to other legal systems (common law, Islamic law) or whether it can be applied in countries with underdeveloped geospatial infrastructure. The Ukrainian example is emblematic of transformational systems, while the analysis is based only on publicly available information without access to the internal technical requirements of the State GeoCadastre (2025).

Third, the study focuses only on technical and data issues and does not address the legal, institutional and organizational issues of implementation. Problems of legal recognition of 3D cadastral objects, organization of work of building and cadastral authorities, issues of staff training and resistance to change are not included in the analysis. The change of use of cadastral information from a means of registration to an analytical planning tool involves cultural and organizational changes, which are accurately described by Krigsholm et al. (2018), but are not considered in our work.

The technological implementation of an integrated system complex cannot achieve the expected efficiency without adequate institutional and legal support. Legislative recognition of three-dimensional land cadastre objects, definition of vertical legal competences, and interagency coordination remain priority challenges. Interaction between urban planning, land registration, and property rights registration authorities at the national and regional levels is critical.

## 6. Implications and further research

The article creates a conceptual integration framework for automated management of the road infrastructure cadastre using a systematic combination of BIM (IFC 4.3), GIS (CityGML 3.0), 3D cadastre (LADM Edition II) and machine learning technologies. The key theoretical achievement is the development of a single workflow, i.e. from design to cadastral registration and automated assessment, which does not require traditional data separation between engineering, geospatial and cadastral systems.

The proposed LADM extension, which includes the classes `LA_RoadInfrastructureUnit`, `LA_RoadSegment` and `LA_VerticalExtent`, applies a formalization of the description of multi-level road infrastructure in a context where legal space (right of way, typically 3-8 meters wider than the physical road surface) and physical space (roadbed) are distinct. The seven-step cadastral registration process, which supports automated geometry extraction from ready-made BIM models, geometry and semantics validation, 3D cadastral object creation and association with existing records, suggests a possible reduction in registration time of 60-80 % compared to traditional surveying tools, but this estimate needs to be empirically verified.

Cases were conducted, which showed that the system can be scaled to systems with different levels of digital maturity. Operational 3D pilots, full API access and high-quality BIM data (LOD3) of the Dutch system can be automated (85-90% of the workflow) with an expected coordinate transformation accuracy of  $\pm 5$  cm and semantics of 90-95 %. The Spanish system has 60-70% automation potential with an accuracy of  $\pm 15$  cm, is INSPIRE compatible and moderately digitalized. The cross-border case of Belgium and Germany showed the criticality of any harmonization of different coordinate systems (Lambert 72 vs. ETRS89 UTM 32N) and an expected accuracy of preserving semantics of 70-75%. The Ukrainian transformation system is able to apply this framework in stages with 40-50 % initial automation, especially when it comes to rebuilding infrastructure after the war. Theoretically, the estimation integration model based on a multifactorial framework (location, physical, legal, infrastructure factors) and the XGBoost (2025) algorithm allows the use of detailed BIM characteristics (surface condition, materials, geometry) to improve the accuracy of mass estimation to a MAPE of 7-10% with high-quality data and 13-17%

with systems with limited transaction databases, which is 15-25% higher than traditional methods.

A comparative analysis of national systems with different levels of digital transformation confirms the fundamental scalability of the proposed integration framework. This scalability is ensured by the modular organizational structure of the architecture, which allows for adaptation to various institutional and technological contexts. At the same time, the results of the study demonstrate that technological flexibility alone does not guarantee the successful practical implementation of the system. A critical factor is the parallel institutional synchronization and coordination of the pace of implementation of various components of the system at the organizational level. Harmonizing the dynamics of BIM methodology adaptation in road construction with the processes of cadastral infrastructure transformation is crucial to avoiding fragmented solutions.

A key weakness of the study is that it is theoretical and has not been empirically tested on real projects, existing cadastral databases and transaction data. Measurements of all accuracy indicators are based on extrapolation of literature sources and evaluation of technical specifications, but not under controlled conditions. The discussion is limited to cases in Europe and the continental legal tradition, which limits the generalizability of the findings to other jurisdictions. The study focuses only on technical issues and not on legal, institutional and organizational issues related to implementation.

The development of open-source tools for IFC→LADM transformation with a graphical interface will lower technical barriers and allow for widespread testing. Using IoT sensors to monitor the condition of the road surface in real time will make this structure not only dynamic, but also a dynamic digital twin with automatically updated assessment models. This is an important direction for transferring the methodology to other types of linear infrastructure and exploring legal means of recognizing 3D cadastral objects in national legislation.

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