3D Land Administration in line with the Spatial Development Lifecycle

Kalogianni, E.

DOI
10.71690/abe.2025.19

Publication date
2025

Document Version
Final published version

Citation (APA)
Kalogianni, E. (2025). *3D Land Administration in line with the Spatial Development Lifecycle*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.71690/abe.2025.19

3D Land Administration in line with the Spatial Development Lifecycle

Eftychia Kalogianni

3D Land Administration in line with the Spatial Development Lifecycle

Eftychia Kalogianni

TOC

A+BE | Architecture and the Built Environment | TU Delft BK

25#19

Design | Sirene Ontwerpers, Véro Crickx

Keywords | 3D land administration, LADM, surveying, BIM, interoperability

ISBN 978-94-6518-109-7
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.71690/abe.2025.19

3D Land Administration in line with the Spatial Development Lifecycle

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Thursday 2 October 2025 at 12:30 o'clock

by

Eftychia KALOGIANNI
Master of Science in Geoinformatics
National Technical University of Athens, Greece
Master of Science in Geomatics
Delft University of Technology, the Netherlands

TOC

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus,	chairperson
Prof.dr.ir. P.J.M. van Oosterom	Delft University of Technology, promotor
Prof.dr. E. Dimopoulou	National Technical University of Athens, promotor
Em.Prof.dr.ir. C.H.J. Lemmen	University of Twente, promotor

Independent members:

Prof.Dr.-Ing. J. Blankenbach	RWTH Aachen University, Germany
Prof.dr. A.R. Pereira Roders	Delft University of Technology
Prof.mr.dr.ir. J. A. Zevenbergen	University of Twente
Prof.dr.techn. S. Zlatanova	University of New South Wales, Australia

Reserve members:

Prof.dr. M. Overend	Delft University of Technology

This research has received funding from the European GNSS Agency under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870231 (Galileo Improved Services for Cadastral Augmentation Development On-field Validation - GISCAD-OV).

Acknowledgements

Thank you / dankjewel / ευχαριστώ

My interest in Land Administration dates back to my early university years, when I first realised how crucial it is to establish accurate, effective, and up-to-date Land Administration Systems—accessible online and enhanced by state-of-the-art technology. Since then, I have had the privilege of working with and learning from some of the most inspiring people I know, whose guidance and support have profoundly shaped this dissertation. The real-world impact of this research—particularly in global standardisation initiatives and practical implementations—has been among the most rewarding aspects of this journey.

Moving to Delft and working with Prof. Peter van Oosterom has been one of the most defining moments of this journey. This dissertation would not have been the same without his outstanding mentoring, continuous support, and the trust and confidence he placed in me. Endless discussions and brainstorming sessions often led to new directions—always a risk to open yet another chapter in the PhD, yet one that proved worthwhile every single time. Away from strict timelines of supervisory time, he offered his ideas and time to refine the topic many times, disscuss future directions, write funding proposals and prepare conference presentations or edit journal publications. His patience and guidance helped me push through moments when I thought I had reached a dead end, while his encouragement gave me the space to grow and the freedom to express myself. I will remain forever grateful for this continuous collaboration.

I also want to express my deepest gratitude to my supervisor and promotor, Prof. Efi Dimopoulou, who has been a guiding presence since my diploma thesis at NTUA in 2012, when she first introduced me to the topic of Land Administration. Her openness to discussion, constant encouragement, and unwavering support throughout this journey have been invaluable. More than a supervisor, she has been a thoughtful listener and trusted advisor.

Together with Peter and Efi, I owe special thanks to Prof. Christiaan Lemmen, my third supervisor and promotor. He provided guidance and encouragement even in moments when my motivation waned, always helping me refocus on the essential issues. Sharing travels abroad and participating in ISO and OGC meetings with him have been both a pleasure and deeply productive experiences.

To these three supervisors, promotors, and true mentors—thank you. I owe you a great debt of gratitude for everything I have learned from you and for the researcher I become.

I would also like to extend my sincere thanks to all members of the Section Digital Technlogies, including my colleagues from the former GIS Technology group: Dr. Martijn Meijers, Edward Verbree, Marianne de Vries, and Wilko Quak, as well as Assoc. Prof. Dr. Michela Turrin and the late Prof. Sevil Sariyildiz, who so unexpectedly passed away. It has been both an honour and a pleasure to collaborate with each of you. I am also grateful to the Secretariat of the former OTB and to the staff of the Architectural Engineering and Technology department for their administrative support throughout my PhD.

A special thanks goes to Dr. Abdullah Kara and Dr. Abdullah Alattas—the closest companions of this journey and, above all, dear friends.

Balancing the demands of a PhD with professional responsibilities and personal life has indeed been a challenge, yet one that has strengthened both my adaptability and persistence. As a part-time doctoral candidate, I have experienced various professional stages along the way, each contributing in direct and indirect ways to the development of this dissertation. I am grateful to my colleagues at Future Insight for their support, discussions, and stimulating brainstorming sessions. Sharing part of this journey with you has been a true pleasure—especially during the travels to Zwolle.

I would also like to thank my two life-long friends gained in the Netherlands, Rusne and Sandra. I consider myself truly fortunate to have you by my side.

I would have achieved nothing without my family, to whom no words can adequately convey my gratitude and appreciation. I owe the deepest thanks to my parents, Anastasia and Stavros, who made me the person I am today, giving me roots to always remember where I started and wings to explore new horizons. Their unwavering support and encouragement, regardless of the circumstances, have been a constant source of strength. I am also deeply grateful for the love, support, and blessings of my sister, Olympia-Christina, and my brother, Lefteris, who are always open for vivid discussions, brainstorming, and ready to help in any circumstance.

Finally, I extend my heartfelt gratitude to my husband, Stathis—my partner in both personal and professional life—who has stood by my side from the very beginning of this journey. Thank you for everything you have done for me and for our little family; your presence, trust, and support have made all the difference.

Contents

TOC

List of Tables

List of Figures

List of abbreviations

ADR	Action Design Research
AECOO	Architecture, Engineering, Construction, Owner Operator
API	Application Programming Interface
AR	Augmented Reality
BCF	BIM Collaboration Format
BIM	Building Information Modelling
bsDD	buildingSMART Data Dictionary
bSI	buildingSMART International
CBE	Circular Built Environment
CCDM	Core Cadastral Domain Model
CD	Committee Draft
CEN	European Committee for Standardisation
CLGE	Council of European Geodetic Surveyors
COBie	Construction Operation Building Information Exchange
CSDM	Cadastral Survey Data Model
CSL	Conceptual Schema Language
DBMS	Database Management Systems
DCDB	Digital Cadastral Database
DIS	Draft International Standard
DOP	Dilution of Precision
DSR	Design Science Research
DT	Digital Technologies
EC	European Commission
ETL	Extract, Transform, Load
FAIR	Findable, Accessible, Interoperable and Reusable
FELA	Framework for Effective Land Administration
FFP	Fit-For-Purpose
FFP-LA	Fit-for-Purpose Land Administration
FIG	International Federation of Surveyors

>>>

GDOP	Geometric Dilution of Precision
GeoBIM	Geographic Information Systems and Building Information Modelling
GII	Geographical Information Infrastructure
GIS	Geographic Information Systems
GISCAD-OV	Galileo Improved Services for Cadastral Augmentation Development On-field Validation
GLII	Global Land Indicator Initiative
GLTN	Global Land Tool Network
GML	Geography Markup Language
GNSS	Global Navigation Satellite Systems
HAS	High Accuracy Services
HC	Hellenic Cadastre
HRSI	High Resolution Satellite Imagery
HVD	High value datasets
ICSM	Australia and New Zealand Intergovernmental Committee on Surveying and Mapping
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IFD	International Framework for Dictionaries
IGIF	Integrated Geospatial Information Framework
IHO	International Hydrographic Organisation
ILMS	International Land Measurement Standard
INSPIRE	Infrastructure for Spatial Information in the European Community
IoT	Internet of Things
IPMS	International Property Measurement Standards
IPR	Intellectual Property Rights
IS	International Standard
ISO	International Organisation for Standardisation
IT	Information Technology
JSON-FG	Features and Geometries JSON
KML	Keyhole Markup Language
LA	Land Administration
LADM	Land Administration Domain Model
LADM_SP	Spatial plan Information package
LADM_VM	Valuation Information package
LAS	Land Administration System
LCML	Land Cover Meta Language
LoD	Levels of Detail
LGAF	Land Governance Assessment Framework
LPIS	Land Parcel Identification Systems
OGC	Open Geospatial Consortium

>>>

TOC

MAST	Mobile Applications to Secure Tenure
MDA	Model-Driven Architecture
MIM	Minimal Interoperability Mechanisms
MVD	Model View Definition
MS	EU Member States
NGOs	Non-Governmental Organisations
NLIS	National Land Information System
NMCA	National Mapping and Cadastral Authority
NURBS	Non-Uniform Rational B-Splines
NWIP	New Work Item Proposal
OASC	Open & Agile Smart Cities & Communities
OMG	Object Management Group
OSR	Observation Space Representation
PLR	Public Law Restriction
PPI	Pivotal Points of Interoperability
PPP	Precise Point Positioning
PPP-AR	Precise Point Positioning-Ambiguity Resolution quick convergence
RICS	Royal Institute of Chartered Surveyors
RRF	Recovery and Resilience Facility
RRRs	Rights, Restrictions, and Responsibilities
RTK	Real-Time-Kinematic
RQ	Research Question
SCC	Standards Council of Canada
SDI	Spatial Data Infrastructure
SDL	Spatial Development Lifecycle
SHACL	Shapes Constraint Language
SII	Spatial Information Infrastructure
SKOS	Simple Knowledge Organisation Systems
SOA	Service Oriented Architecture
SOLA	Solutions for Open Land Administration
SOLAS	International Convention for the Safety of Life at Sea
SOSA	Sensor, Observation, Sample, and Actuator
SSR	State Space Representation
STDM	Social Tenure Domain Model
SWG	Standards Working Group
TC	Technical Committee
UAV	Unmanned Aerial Vehicle
ULA	Underground Land Administration
UN	United Nations

>>>

UNCLOS	United Nations Convention on the Law of the Sea
UNECE	United Nations Economic Commission for Europe
ECOSOC	United Nations Economic and Social Council
UBM	Unified Building Model
UNGGIM	United Nations Committee of Experts on Global Geospatial Information Management
UML	Unified Modelling Language
VHRSI	Very High-Resolution Satellite Imagery
VR	Virtual Reality
WB	World Bank
WD	Working Drafts
WFMS	Workflow Management System
2.5D	Two-and-a-half Dimensional
2D	Two Dimensional
3D	Three Dimensional

Summary

Land administration (LA) is a cornerstone for sustainable development, environmental management, and inclusive governance. As the World Bank states "*with registered property rights and transparent rules, people can use their land as collateral to access private credit, which can then be invested in their businesses, homes, and livelihoods. In urban areas in particular, digital land records can boost credit access by 10.5% on average, rising to 15% over time*"[1]. However, many Land Administration Systems remain fragmented, paper-based, and technologically outdated. These limitations hinder their capacity to address pressing challenges such as rapid urbanisation, climate risk, and informal tenure, thereby constraining transparent governance, equitable land access, and data-driven spatial planning.

In addressing this, **this PhD dissertation investigates the effective integration of 3D LA into the broader Spatial Development Lifecycle (SDL) context, placing particular emphasis on data reuse, interoperability, and alignment with international standards.** It addresses the pressing need to integrate 3D spatial data and legal frameworks into evolving LASs that more accurately reflect the complexity of contemporary urban environments. By engaging with global priorities such as sustainable urban development, land tenure security, and the digital transformation of governance, this research provides practical tools and strategic insights relevant to both developed and developing countries.

The research is structured around the **main Research Question: "How to design, develop and evaluate efficient 3D Land Administration in support of the Spatial Development Lifecycle."** To answer this, seven sub-questions are systematically examined. While the research focuses primarily on the technical dimensions of this challenge, it acknowledges that legal and organisational frameworks are essential enabling conditions. Employing the Design Science Research methodology, the study integrates qualitative and quantitative approaches to develop an information model for cadastral surveying. This model supports the integration of both professional and crowdsourced 2D and 3D survey techniques, in alignment with established international standards.

1 https://blogs.worldbank.org/en/digital-development/benefits-of-land-registry-digitization

The **main contributions of this dissertation lie in advancing 3D LA and the ISO19152 Land Administration Domain Model (LADM), with implications for improved LA and broader societal benefits.** The research delivers a suite of standardised models, workflows, and methodologies aimed at enhancing interoperability and promoting lifecycle data reuse within the SDL. Notably, some of the **outcomes of this PhD have been directly incorporated into international standards**, demonstrating a tangible contribution to the ongoing development of globally accepted frameworks. In particular, the dissertation directly contributes to ISO 19152-2:2025 – Land Registration (voted and formally adopted as an ISO standard), and ISO 19152-6 – Implementation (currently under development).

Specifically, the dissertation delivers the following **contributions**:

1. **The introduction of the data circularity concept in 3D LA:** This dissertation introduces the concept of data circularity in 3D LA, advocating for continuous information reuse throughout the SDL and incorporating emerging technologies and diverse data sources.
2. **The design and development of a cadastral surveying information model:** A comprehensive model is developed, which expands upon LADM Edition I's generic references to ISO 19156, offering a more accurate representation of diverse survey methods. The result is included in ISO 19152-2:2025. (*sub-RQ4b*).
3. **The modelling of a standards-based cadastral survey workflow:** A generic workflow integrating professional and crowdsourced 2D/3D survey data acquisition methods is developed, contributing to ISO 19152-6 (*sub-RQ5*).
4. **The design of a methodology for developing LADM-based country profiles:** A structured approach for the development of LADM-based country profiles is designed, contributing directly to ISO 19152-6 (*sub-RQ6*).
5. **The development of 3D spatial profiles for the new international standard ISO 19152-2:** The dissertation introduces refined and standardised 3D spatial profiles for LA, addressing limitations in LADM Edition I and enhancing cross-disciplinary and lifecycle interoperability – the outcome is included in ISO 19152-2:2025 (*sub-RQ3b*).
6. **The development and application of a 3D LA Prototype:** A web-based prototype is developed as a proof of concept, integrating survey and design data sources to validate the proposed models in a dynamic digital environment (*sub-RQ7b*).

The dissertation begins with a comprehensive literature review to define the research problem and establish a strong theoretical foundation. It reviews the state of 2D and 3D LA, compiles a global inventory of 3D LAS as of 2022, and highlights the role of standardisation in supporting data interoperability and reuse across the SDL. Central to this is the LADM, whose evolution and global adoption are examined, including an analysis of LADM-based country profiles and the ongoing development of LADM Edition II.

The SDL is introduced as a unifying framework for managing land-related (and other) data, emphasising data circularity across lifecycle phases. A taxonomy of 3D spatial units is developed, based on previous knowledge, supported by an analysis of data sources from both survey and design processes—most notably through the introduction of the 'BIM Legal' concept. These contributions are grounded in a requirements' analysis and guided by Action Design Research, drawing on expert consultations and international comparative assessments.

Validation of the research outcomes was conducted in two stages: (1) conceptual validation of the refined LADM survey model using real-world use cases from Estonia and Germany, alongside application of the survey workflow in Denmark, Greece, and Colombia; and (2) practical validation through the development of a 3D WebGIS prototype demonstrating the integration of BIM and cadastral survey data. Additional validation was achieved through active contributions to the EU funded H2020 GISCAD-OV project, where part of the survey model was developed. Research outcomes were disseminated through academic publications, international conferences, and active engagement with standardisation bodies, particularly ISO/TC 211 and the Open Geospatial Consortium (OGC).

The results demonstrate the feasibility and benefits of integrating 3D LA into the SDL using internationally standardised models. The LADM survey model supports both professional and participatory approaches, high-accuracy positioning and integration of diverse data sources. The cadastral survey workflow proves adaptable across different legal, institutional and technological environments, and the 3D web prototype demonstrates the ability to visualise and query integrated cadastral and BIM data. Identified challenges, such as georeferencing inconsistencies in IFC are discussed and addressed through targeted solutions.

In conclusion, the dissertation contributes to the development and operationalisation of LADM Edition II. It provides practical tools and workflows for implementing interoperable, scalable, and inclusive 3D LASs aligned with global standardisation efforts. The research outcomes support that advancing 3D LA requires not only technical innovation, but also institutional reform and strong regulatory support.

Future research directions include broader validation of the developed models, further development of a BIM-Legal workflow in line with the developed workflows, integration of emerging technologies (e.g. AI, blockchain), and sustainable data governance approaches to support resilient and efficient LA Systems worldwide.

Samenvatting

Land Administratie is een hoeksteen voor duurzame ontwikkeling, milieubeheer en inclusief bestuur. Zoals de Wereldbank stelt: "*Met geregistreerde eigendomsrechten en transparante regels kunnen mensen hun land als onderpand gebruiken om toegang te krijgen tot particuliere kredieten, die vervolgens kunnen worden geïnvesteerd in hun bedrijven, huizen en in bestaanszekerheid. Met name in stedelijke gebieden kunnen digitale kadastrale registers de toegang tot krediet met gemiddeld 10,5% verhogen, wat in de loop van de tijd kan oplopen tot 15%*". Veel land administratie systemen zijn gefragmenteerd, papiergebaseerd en technologisch verouderd. Deze beperkingen belemmeren het vermogen van deze systemen om uitdagingen aan te pakken, zoals snelle verstedelijking, klimaatrisico's en informeel grondbezit, waardoor transparant bestuur, rechtvaardige toegang tot grond en data-gestuurde ruimtelijke ordening worden belemmerd.

Voor de aanpak van dit probleem **onderzoekt dit proefschrift doeltreffende integratie van 3D LA in de bredere context van de Spatial Development Lifecycle, met bijzondere nadruk op hergebruik van gegevens, interoperabiliteit en afstemming op internationale standaarden.** Het gaat in op de noodzaak om 3D-ruimtelijke gegevens en wettelijke kaders te integreren bij de ontwikkeling van Land Adminitrstatie Systemenen die de complexiteit van hedendaagse stedelijke omgevingen nauwkeuriger kunnen weergeven. Door in te spelen op mondiale prioriteiten zoals duurzame stedelijke ontwikkeling, rechtszekerheid en de digitale transformatie van bestuur, biedt dit onderzoek praktische hulpmiddelen en strategische inzichten die zowel voor ontwikkelde als voor ontwikkelingslanden van toepassing zijn.

Het onderzoek is opgebouwd rond **de hoofdonderzoeksvraag: "Hoe kan een doelmatig 3D-kadaster worden ontworpen, ontwikkeld en geëvalueerd ter ondersteuning van de Spatial Development Lifecycle?**" Om deze vraag te beantwoorden, worden zeven deelvragen systematisch onderzocht. Hoewel het onderzoek zich voornamelijk richt op de technische aspecten van deze uitdaging, wordt erkend dat wettelijke en organisatorische kaders essentiële randvoorwaarden zijn. Met behulp van de Design Science Research-methodologie worden kwalitatieve en kwantitatieve benaderingen gebruikt om een informatiemodel voor kadastrale veldmetingen te ontwikkelen. Dit model ondersteunt de zowel professionele als crowdsourced 2D- en 3D-landmeetkundige technieken, afgestemd op gevestigde internationale standaarden.

De **belangrijkste bijdragen van dit proefschrift liggen in de verdere ontwikkeling van 3D LA en het ISO19152 Land Administration Domain Model (LADM), met implicaties voor verbeterde LA en met bredere maatschappelijke voordelen.** Het onderzoek levert een reeks gestandaardiseerde modellen, workflows en methodologieën op die gericht zijn op het verbeteren van de interoperabiliteit en het bevorderen van het hergebruik van gegevens binnen de SDL. Sommige **resultaten van dit onderzoek zijn rechtstreeks opgenomen in internationale standaarden,** wat een tastbare bijdrage levert aan de ontwikkeling van wereldwijd aanvaarde kaders. Het proefschrift levert met name een directe bijdrage aan ISO 19152-2:2025 – Landregistratie (gepubliceerd als ISO standaard) en ISO 19152-6 – Implementatie (momenteel in ontwikkeling).

Concreet levert het proefschrift de volgende **bijdragen**:

1. **De introductie van het concept van data hergebruik in 3D LA.** Het proefschrift introduceert het concept van hergebruik van data in 3D LA gedurende de hele SDL en integreert opkomende technologieën en diverse gegevensbronnen.
2. **Het ontwerp en de ontwikkeling van een kadastraal landmeetkundig informatie model.** Er wordt een uitgebreid model ontwikkeld, in overeenstemming met ISO 19152-2, dat voortbouwt op de generieke verwijzingen van LADM Edition I naar ISO 19156 en een nauwkeurigere weergave biedt vanhet gerbuik van diverse landmeetkundige methoden (*sub-RQ4b*).
3. **Het modelleren van een op standaarden gebaseerde kadastraal landmeetkundige workflow.** Er wordt een generieke workflow ontwikkeld die professionele en crowdsourced 2D/3D-inwinningsmethoden integreert, wat bijdraagt aan ISO 19152-6 (*sub-RQ5*).
4. **Het ontwerp van een methodologie voor de ontwikkeling van op LADM gebaseerde landenprofielen.** Er wordt een gestructureerde aanpak voor de ontwikkeling van op LADM gebaseerde landenprofielen ontworpen, wat rechtstreeks bijdraagt aan ISO 19152-6 (*sub-RQ6*).
5. **De ontwikkeling van 3D-ruimtelijke profielen voor de nieuwe internationale standaard ISO 19152-2.** Het proefschrift presenteert verfijnde en gestandaardiseerde 3D-ruimtelijke gegevens profielen voor LA, waarbij beperkingen in LADM Edition I worden opgelost en de herbuikbaarheid van gegevens wordt verbeterd – het resultaat is opgenomen in ISO 19152-2 (*sub-RQ3b*).
6. **Het maken en toepassen van een 3D LA-prototype.** Er wordt een webgebaseerd prototype ontwikkeld als proof of concept, waarin onderzoeks- en ontwerpgegevensbronnen worden geïntegreerd om de voorgestelde modellen in een dynamische digitale omgeving te valideren (*sub-RQ7b*).

Het proefschrift begint met een literatuuronderzoek om het onderzoeksprobleem te definiëren en een sterke theoretische basis te leggen. Het geeft een overzicht van de stand van zaken op het gebied van 2D- en 3D-LA, stelt een wereldwijde inventarisatie op van 3D-LAS per 2022 en benadrukt de rol van standaardisatie bij het ondersteunen van gegevensinteroperabiliteit en hergebruik binnen de SDL. Centraal hierbij staat het LADM, waarvan de ontwikkeling en wereldwijde acceptatie worden onderzocht, inclusief een analyse van op LADM gebaseerde landenprofielen en de voortdurende ontwikkeling van LADM Edition II.

De SDL wordt geïntroduceerd als een uniform kader voor het beheer van landgerelateerde (en andere) gegevens, waarbij de nadruk ligt op hergebruik van gegevens gedurende de verschillende levenscyclusfasen. Er wordt een taxonomie van 3D-ruimtelijke eenheden ontwikkeld op basis van eerdere kennis, ondersteund door een analyse van gegevensbronnen uit zowel onderzoeks- als ontwerpprocessen, met name door de introductie van het concept “BIM Legal”. Deze bijdragen zijn gebaseerd op een analyse van de vereisten en er wordt gebruik gemaakt van deskundig advies en internationale vergelijkende beoordelingen.

De validatie van de onderzoeksresultaten vond plaats in twee fasen: (1) conceptuele validatie van het verfijnde LADM-onderzoeksmodel aan de hand van praktijkvoorbeelden uit Estland en Duitsland, naast de toepassing van de landmeetkundige workflow in Denemarken, Griekenland en Colombia; en (2) praktische validatie door de ontwikkeling van een 3D WebGIS-prototype dat de integratie van BIM- en kadastraal landmeetkundige workflow demonstreert. Aanvullende validatie werd bereikt door actieve bijdragen aan het door de EU gefinancierde H2020 GISCAD-OV-project, waar een deel van het onderzoeksmodel werd ontwikkeld. De onderzoeksresultaten werden verspreid via academische publicaties, internationale conferenties en actieve betrokkenheid bij standaardisatie organisatsies, met name ISO/TC 211 en het Open Geospatial Consortium.

De resultaten tonen de haalbaarheid en voordelen aan van de integratie van 3D LA in de SDL met behulp van internationaal gestandaardiseerde modellen. Het LADM-gebaseerd landmeetkundig model ondersteunt zowel professionele als participatieve benaderingen, zeer nauwkeurige positionering (bijv. GNSS met Galileo HAS) en de integratie van diverse gegevensbronnen. De voorgestelde workflow voor kadastrale metingen blijkt aanpasbaar te zijn aan verschillende juridische, institutionele en technologische omgevingen, en het 3D-webprototype toont de praktische mogelijkheid om geïntegreerde kadastrale en BIM-gegevens te visualiseren en te doorzoeken. Uitdagingen die tijdens de ontwikkeling van het prototype zijn vastgesteld, zoals inconsistenties in de georeferentie van IFC-modellen, worden besproken en aangepakt met gerichte oplossingen.

TOC

Concluderend levert het proefschrift een belangrijke bijdrage aan de ontwikkeling en operationalisering van LADM Edition II. Het biedt praktische tools en workflows voor de implementatie van interoperabele, schaalbare en inclusieve 3D LAS'en die aansluiten bij wereldwijde standaardisatie-inspanningen. De onderzoeksresultaten geven aan dat de ontwikkeling van 3D LA niet alleen technische innovatie vereist, maar ook institutionele hervormingen alsmede krachtige ondersteuning door regelgeving.

Toekomstige onderzoeks voorstellen omvatten een bredere validatie van de ontwikkelde modellen, verdere ontwikkeling van een ‘BIM-Legal-workflow’ afgestemd op vastgestelde processen, integratie van opkomende technologieën (bijv. AI, blockchain) en duurzame benaderingen van gegevensbeheer ter ondersteuning van veerkrachtige en doelmatige LA-systemen wereldwijd.

Περίληψη

Η **Διοίκηση Γης** (Land Administration) αποτελεί βασικό πυλώνα για τη βιώσιμη ανάπτυξη, τη διαχείριση του περιβάλλοντος, τη δίκαιη και συμμετοχική διακυβέρνηση. Πολλά **Συστήματα Διοίκησης Γης** παγκοσμίως εξακολουθούν να βασίζονται σε δισδιάστατες προσεγγίσεις και έντυπα αρχεία, γεγονός που δεν επαρκεί πλέον για να αποτυπώσει τη σύγχρονη πολυπλοκότητα. Η επιταχυνόμενη αστικοποίηση, οι εντεινόμενοι κλιματικοί κίνδυνοι και οι άτυπες μορφές ιδιοκτησίας δημιουργούν την ανάγκη για τρισδιάστατη καταγραφή των εμπράγματων δικαιωμάτων και σύνθετων κατασκευών. Με τον τρόπο αυτό διασφαλίζεται η διαφάνεια στη διακυβέρνηση, η ισότιμη πρόσβαση στη γη και η αποτελεσματική υποστήριξη του πολεοδομικού σχεδιασμού και των διαδικασιών λήψης αποφάσεων.

Η διεθνής επιστημονική κοινότητα έχει αναπτύξει σημαντικό ερευνητικό έργο και πιλοτικές εφαρμογές για την τρισδιάστατη διοίκηση γης, αναδεικνύοντας τα πλεονεκτήματά της: μεγαλύτερη νομική ασφάλεια (των δικαιωμάτων), ακριβέστερη αποτίμηση και ενίσχυση του χωρικού σχεδιασμού σε τρεις διαστάσεις. **Η παρούσα διδακτορική διατριβή ανταποκρίνεται σε αυτές τις προκλήσεις, διερευνώντας την αποτελεσματική ενσωμάτωση της τρισδιάστατης διοίκησης γης στον κύκλο ζωής της χωρικής ανάπτυξης ενός ακινήτου (Spatial Development Lifecycle).** Έμφαση δίνεται στην επαναχρησιμοποίηση δεδομένων, τη διαλειτουργικότητα και την εναρμόνιση με διεθνή πρότυπα.

Το διεθνές πρότυπο **ISO 19152 – LADM (Land Administration Domain Model) αποτελεί κεντρικό πυλώνα της έρευνας.** Σήμερα βρίσκεται σε φάση αναθεώρησης και ανάπτυξης της δεύτερης έκδοσης του από την Τεχνική Επιτροπή 211 του ISO. Η νέα έκδοση αποτελείται από έξι μέρη: (1) Generic Conceptual Model, (2) Land Registration, (3) Marine Georegulation, (4) Valuation Information, (5) Spatial Plan Information, και (6) Implementation Aspects. Τα μέρη 1 έως 5 έχουν ήδη δημοσιευθεί ως διεθνή πρότυπα στο διάστημα 2024–2025, ενώ το Μέρος 6 αναπτύσσεται σε συνεργασία με το Open Geospatial Consortium (OGC). Η παρούσα διατριβή συνεισφέρει ουσιαστικά στην ανάπτυξη του Μέρους 2 (ISO19152-2:2025 - Land Registration), στο οποίο έχουν ενσωματωθεί αποτελέσματα της έρευνας, επιβεβαιώνοντας τον επιστημονικό και πρακτικό αντίκτυπό της.

Η έρευνα απαντά στο βασικό ερώτημα «*Πώς σχεδιάζεται, αναπτύσσεται και αξιολογείται ένα αποτελεσματικό, τρισδιάστατο Σύστημα Διοίκησης Γης, προκειμένου να υποστηρίζει τον κύκλο της χωρικής ανάπτυξης;*». Η διατριβή υιοθετεί τη μεθοδολογία *Design Science Research*, συνδυάζοντας ποιοτικές και ποσοτικές προσεγγίσεις.

Η **διατριβή συνεισφέρει σημαντικά στα εξής**:

1. Την εισαγωγή **της έννοιας της κυκλικότητας δεδομένων στην τρισδιάστατη διοίκησης γης**, δηλαδή της συνεχούς επαναχρησιμοποίησης πληροφοριών σε όλα τα στάδια του κύκλου ζωής, ενσωματώνοντας αναδυόμενες τεχνολογίες όπως το Building Information Model (BIM), ψηφιακά δίδυμα πόλεων (Digital Twins), GNSS υψηλής ακρίβειας και συμμετοχικές διαδικασίες.
2. **Τη μοντελοποίηση ενός τυποποιημένου πληροφοριακού μοντέλου τοπογραφικών μετρήσεων για εφαρμογές διαχείρισης γης**, το οποίο ενσωματώνεται στο διεθνές πρότυπο ISO 19152-2:2025 – Land Registration.
3. **Το σχεδιασμό μιας τυποποιημένης ροής εργασίας για τοπογραφικές μετρήσεις σε εφαρμογές διαχείρισης γης,** που υποστηρίζει τόσο 2D όσο και 3D δεδομένα και συμβάλλει στην ανάπτυξη του διεθνούς προτύπου ISO 19152-6-Implementation Aspects.
4. **Την ανάπτυξη μεθοδολογίας για τη δημιουργία εθνικών προφίλ (country profiles) βασισμένων στο LADM,** ώστε να εξασφαλιστεί η εφαρμογή του σε διαφορετικά νομικά και θεσμικά πλαίσια.
5. **Τη μοντελοποίηση τυποποιημένων τρισδιάστατων χωρικών προφίλ (spatial profiles)** που περιγράφουν (γεωμετρικά σύνθετες) χωρικές μονάδες και ενισχύουν τη διαλειτουργικότητα μεταξύ συστημάτων και εμπλεκόμενων φορέων.
6. **Την ανάπτυξη πιλοτικής διαδικτυακής εφαρμογής 3D WebGIS για τη διαχείριση γης** που αποδεικνύει στην πράξη, την ενοποίηση δεδομένων τοπογραφικών μετρήσεων και δεδομένων που προέρχονται από το στάδιο του σχεδιασμού (π.χ. BIM).

Η επικύρωση των αποτελεσμάτων της έρευνας πραγματοποιήθηκε μέσω μελετών περίπτωσης σε διάφορες χώρες. Συγκεκριμένα, με τοπογραφικές μετρήσεις που έγιναν στην Εσθονία και τη Γερμανία επικυρώθηκε το τυποποιημένο πληροφοριακό μοντέλο τοπογραφικών μετρήσεων, ενώ στη Δανία, την Ελλάδα και την Κολομβία αξιολογήθηκε η εφαρμογή της ροής εργασιών για τοπογραφικές μετρήσεις. Η πρακτική εφαρμογή των αποτελεσμάτων αξιολογήθηκε μέσω της ανάπτυξης του 3D WebGIS.

Μέρος των αποτελεσμάτων της διατριβής έχει ήδη ενσωματωθεί σε διεθνή πρότυπα. Συγκεκριμένα, το τυποποιημένο πληροφοριακό μοντέλο τοπογραφικών μετρήσεων για εφαρμογές διαχείρισης γης και τα τυποποιημένα τρισδιάστατα χωρικά προφίλ έχουν συμπεριληφθεί στο ISO 19152-2:2025. Παράλληλα, η μεθοδολογία για τη δημιουργία εθνικών προφίλ βασισμένων στο LADM, καθώς και η τυποποιημένη ροή εργασίας για τοπογραφικές μετρήσεις σε εφαρμογές διαχείρισης γης συνεισφέρουν στη διαμόρφωση του υπό εκπόνηση ISO 19152-6.

Συνολικά, η συμβολή της διατριβής είναι διπλή: σε εννοιολογικό επίπεδο, εισάγει νέα μοντέλα και μεθοδολογίες, όπως η έννοια της κυκλικότητας δεδομένων και η ανάπτυξη εθνικών προφίλ βάσει του LADM, ενώ πρακτικά παρέχει εργαλεία και εφαρμογές που έχουν ήδη αναγνωριστεί από διεθνείς οργανισμούς όπως ISO και OGC. Τέλος, προτείνονται κατευθύνσεις για μελλοντική έρευνα, όπως η ενσωμάτωση τεχνητής νοημοσύνης, blockchain, βιώσιμων προσεγγίσεων διακυβέρνησης δεδομένων και BIM-legal ροές εργασίας, με στόχο τη δημιουργία ανθεκτικών, διαφανών και αποτελεσματικών συστημάτων διαχείρισης γης σε παγκόσμιο επίπεδο.

1 Introduction

Imagine that you share the ownership of a mixed-use building in Ioannina (Greece) together with your sister and your brother. In this building, the five lower floors accommodate super-markets and other commercial stores, the next five floors educational offices, while large apartments, with privately owned balconies and shared storage areas are located on the remaining floors. There is also a mortgage established via an Italian bank. *It is 2045 and the fourth Recovery and Resilience Facility (RRF) by EU aids in the renovation of old buildings in medium-sized city centres throughout Europe, in order to be transformed into hotel units.*
One of the important prerequisites is that the biggest share of the ownership of the buildings belongs to young people (max 22 years old) so that the youngest generation emerge stronger and more resilient. Therefore, together with your siblings you decide to transfer the 2/3 of your ownership rights to your children and subsequently, there is need to split the ownership to share the rights with the new owners.

As the existing topographic drawing of the parcel and the building is in PDF format and needs to be in line with the most recent technical specifications, you request from a professional surveyor to survey the parcel and the building using the state-of-the art equipment. During the preparation of the application at the RRF, you realise that it is mandatory to submit all drawings and building permits in accordance with ISO standards and specifically, all the information need to be stored in the Industry Foundation Class (IFC) used to describe the Building Information Model (BIM).
As the initial drawings of the building and the permit are also in PDF, you request from an architect to prepare the detailed 3D BIM model. You request that apart from the BIM model common spaces (Figure 1.1.a), he will create a 3D model that will display the 3D legal spaces and distinguish between the private and common spaces (Figure 1.1.b), so that it will be possible to visualise the legal spaces of a single apartment (Figure 1.1.c). Furthermore, the BIM shall be accompanied with the respective floor plan in a 2D view (Figure 1.1.d), which will be generated with the new set of 3D survey observations that the surveyor captured using a laser scanner.

The architect prepares the 3D model and the notary makes the split of the legal spaces, from you and your siblings to your children in a 3D view, using the BIM model. Then, the newly created 3D legal spaces are further enriched with legal information and together with the new title and the rest of the documents are submitted to the Hellenic Cadastre. The new set of 3D survey observations is also submitted in a standardised structure. Similarly, the BIM model is then submitted in the Municipal Urban Planning Authority to issue the new building permit due to the change of the building use and the construction works needed. Following all the procedures and obtaining the necessary permits, an updated BIM model of the building will be submitted to the RRF to request funding.

What is needed to realise the scenario where:

A the same 3D BIM model is used as basis for the 3D legal spaces creation, the building permit issuance, the mortgage and the funding? Which standards shall be used to enable interoperability?

B the stakeholders involved (architect, notary, Cadastre, funding institutions, Urban Planning Authority), located in different countries, shall communicate, exchange information and use the same terminology?

C the 3D survey-related data is stored in the database in a standardised way?

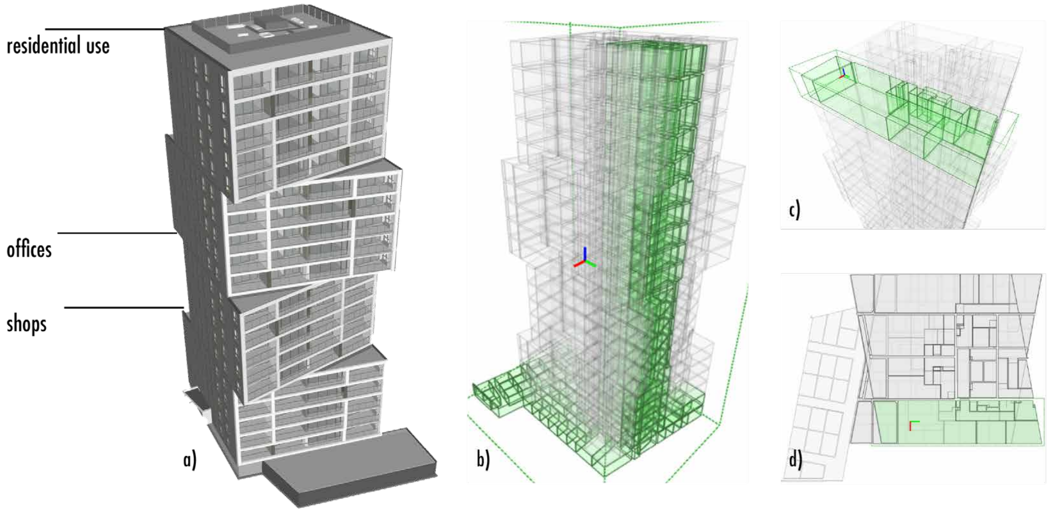

FIG. 1.1 a) the original, architectural BIM model, b) the 'BIM Legal' view – shared 3D legal spaces of the building, c) the 3D legal (private) spaces of a single apartment, d) the corresponding 2D view of the apartment

In most countries, LA practices predominantly rely on Land Administration Systems (LAS) where legal property boundaries are depicted on 2D maps and drawings. This approach often seems inadequate for effectively managing the complexities of urban environment, interleaving legal, organisational and technical challenges. Nevertheless, as far as they delineate land, water, air and underground interests, they are inherently 3D and to be able to cope with the societal trends, those systems need re-engineering to support 3D. There are different sources of 3D data that can be used as input for 3D LA, among them BIM and survey observations are of the interest of this dissertation.

The motivation for this PhD research stems from outdated 2D LA representations, the limited reuse of existing data within the LA domain, and the absence of a standardised framework (both in terms of methodology and model) for cadastral surveys and the storage of 3D survey. The goal is to develop a process for reusing information within the context of the Spatial Development Lifecycle, with an emphasis on 3D LA.

Section 1.1 of this chapter lays the groundwork for the detailed exploration and analysis that follows, starting with the research questions and the methodology presented in **section 1.2,** which also includes the core terminology used. Following this, the research setup within which the research is situated is presented in **section 1.3**. **Section 1.4** highlights the key contributions of this research and sets its boundaries by acknowledging the broader context within which the research lies without providing novel contribution to these research topics. Concluding, **section 1.5** provides a detailed outline of the dissertation, serving as a roadmap for the reader, highlighting the logical progression of the research narrative. Finally, **section 1.6** presents the list of relevant, own publications associated with the research, which are (partly) reused in this research.

1.1 Setting the scene

The importance of land is highlighted in several global documents and frameworks, underscoring its critical role in sustainable development, governance, social equity and management of natural resources. Namely, the United Nations Agenda for Sustainable Development Goals (SDGs) (World Bank, 2018) places land and land tenure as central in several SDGs; the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries, and Forests (VGGTs), initiated by United Nations Food and Agriculture Organization (UN FAO) (FAO, 2012), emphasise the importance of secure land rights; the New Urban Agenda (NUA) from Habitat III (UN-Habitat, 2016) recognises the crucial role of Land Administration (LA) in creating resilient cities, while the Framework for Effective Land Administration (UN-GGIM, 2020) provides the framework for effective LA.

Even though, those drivers are global, LA is subject to national policies and contributes to the implementation of those policies (UN ECE, 1996). A robust LA contributes to foster local economies by establishing a clear and efficient framework for managing land resources, property rights, land use, land valuation and taxation and spatial plan information. It has been recognised that the most successful economies of the world clearly benefit from a land management capacity delivered by well-established Land Administration Systems (LASs) (Williamson et al., 2010). Even though, cadastral research gained momentum during the last few decades (Çağdaş et al., 2011), today the escalating demand for space within built-up areas underscores the need for sustainable (two and three dimensional) LA solutions that effectively manage the utilisation of space both below and above the earth's surface. In this context, the "*urban millennium*" (UNFPA, 2007) creates challenges and opportunities for LA, reflecting a pivotal shift in global demographics and equitable distribution of land resources.

Despite this, the recording of land and property rights, along with associated restrictions and responsibilities, remains reliant on conventional 2D cadastral maps and (building) floor plans and registration, as well as related legislation. While this approach has served its purpose well in the past, it is insufficient for addressing the complexities of contemporary urban land use and the multi-layered nature of property rights and restrictions. Complex spatial arrangements, including multi-storey buildings, underground facilities and layered infrastructures cannot be adequately represented through such traditional 2D systems, leading to potential legal ambiguities and management challenges. Beyond efficiently managing the existing situation, 3D LAS could facilitate space utilisation with a forward-looking approach to (urban) planning, while continuously support also 2D cases. By leveraging detailed 3D insights by such systems, it is expected that domain professionals and policymakers will enhance the efficiency and sustainability of urban environments, while also promoting equitable access to resources and infrastructure.

Although the statement on the *vision of Cadastre 2014* (Kaufmann et al., 1998) does not mention 3D cadastre explicitly, it encourages countries to accelerate their efforts to provide a complete overview of land (in all dimensions), including public rights and restrictions. In 2014, the International Federation of Surveyors (FIG) enhanced this vision through "*Cadastre 2014 and Beyond*" (Steudler, 2014) emphasising the importance of integrating legal documentation with a spatial representation and advocating for a standardised data model for LA. In this scene, advancing LA to encompass 3D rights and restrictions enhances the resilience of the built environment, while reducing risks associated with natural disasters, climate change, and human activities. 3D LA encompasses the elements of 2D LA, but extends further to address the complexities and requirements of modern urban environments.

Another key driver to move forward towards 3D LA is the opportunity to leverage technological advancements to efficiently serve the complexities of contemporary built environment. Today, digital technologies (DT) offer robust tools and methodologies that facilitate the collection, design, storage, maintenance, analysis, visualisation and dissemination of 3D spatial data that positions them as facilitators for a feasible and cost-effective transition towards 3D (Shiu et al., 2021). Expanding the focus beyond just the (land) registration phase, these technologies play a role across the entire Spatial Development Lifecycle (SDL) —from planning, designing and surveying to permits' provisioning, constructing, using and maintaining. Namely, exploration and utilisation of emerging geospatial technologies, such as blockchain technologies (Bennett et al., 2019; Müller et al., 2019), smart contracts (Bennett et al., 2021a), crowdsourced land information, imagery delivered by various platforms (Very High Resolution Satellite Imagery - VHRSI, High Resolution Satellite Imagery - HRSI, Lidar, Unmanned Aerial Vehicle - UAV), digital twins, BIM – all backed by Fit-for-Purpose Land Administration (FFP-LA) – support LA to accelerate digitally (FAO, UNECE and FIG, 2022). By incorporating 3D capabilities at each stage of the SDL, DT enhance the precision, efficiency, comprehensibility and use of (2D and 3D) spatial data management. This broad application not only streamlines processes, but also improves decision-making and resource allocation across various sectors, ensuring that LASs are robust, responsive, and aligned with the evolving demands of urban development and sustainable environmental management.

The SDL (Kalogianni et al., 2020a) is a dynamic and iterative process, requiring ongoing engagement with stakeholders, adaptive management practices, and a commitment to sustainable and resilient development principles. Currently, the disciplines involved in the different phases of this SDL are quite autonomous, and the respective experts are using custom-made, independent methodologies and workflows (Kalogianni et al., 2020a). This existing, fragmented situation (Verhulst, 2021) has proven slow and expensive, with inconsistent datasets and duplicates for the same spatial units through different phases of their lifecycle.

Today, in our networked society and economy, there is increased attention given to the re-usability of data, which also applies in LA, while originally the focus was solely on unlocking itself. This change underscores a paradigm shift toward the reuse of information developed in the design-phase, such as Building Information Models (BIM) into land administration practices, promoting a more integrated and sustainable approach to LA. Leveraging the detailed data generated during the design and construction of buildings and infrastructure (as-designed and as-built) can greatly enhance the accuracy, efficiency, and decision-making in LA. Achieving such a data collaborative approach requires efforts in standardisation, digitalisation, legislation, and stakeholder collaboration, while the potential benefits in the realms of urban planning, valuation, environmental stewardship and economic development are significant (Verhulst, 2021). This approach is more cost efficient, it generates fresh insights for better policy and overcome inequalities and asymmetries both within and across countries (UN, 2020; World Bank, 2021). In the concept of reusing data responsibly, several countries around the world, have considered the registration of spatial units in 3D by reusing design-phase data, such as BIM models (as it is further discussed in Sections 3.2 and 5.3).

As LA remains a cornerstone of equitable and effective governance across the SDL, BIM serves as an integrated and robust information container, where 3D geometry is a key element, which also encompasses rich and detailed semantic information (Borrmann et al., 2015 and 2018). Beyond the technical advantages, BIM integrates various types of data into a single model, ensuring that stakeholders involved in LA—such as surveyors, planners, architects, engineers and notaries— have access to consistent and comprehensive information. This integration and uniformity are crucial for fostering effective communication and coordination between these groups throughout the entire lifecycle of the spatial unit making BIM a prominent source for 3D LA. Additionally, observations from various data acquisition methods are typically used for LA and can be used as a stand-alone source or complement the BIM data. Combining data from various sources by breaking down silos has the potential to lead to new and innovative insights that can support policy makers take better decisions (Verhulst, 2021).

Looking ahead, the value of spatial information in policymaking, decision-making and action-taking will be increasingly critical in the coming decades (Scott et al., 2017). There is, therefore, an urgent need to develop and adopt standardised, flexible and transparent approaches in LA and land management (Lemmen et al., 2017). Standardisation ensures that data are consistent, reliable, and interoperable across various systems and stakeholders, from surveyors and urban planners to developers and governmental agencies. ISO 19152:2012, the Land Administration Domain Model (LADM) (ISO, 2012) plays a key role as it provides a standardised data model and a common vocabulary, crucial for the global exchange of land-related information. It serves as a reference information model that supports more effective, efficient, and fair LA. While ISO 19152 describes common elements in people-to-land relationships within the LA domain, further customisation is necessary to meet the specific needs of a country or jurisdiction. Therefore, a LADM-based country profile can be developed to reflect the unique characteristics of a nation's LAS.

In the concept of data circularity using standards, combining BIM (especially in Industry Foundation Classes (IFC) format, which is also an ISO standard - ISO 16739-1:2024) with LADM creates a correlation that enhances the understanding of the legal space in condominium ownership (Guler et al., 2022; Petronijević et al., 2021).

The aforementioned give background and motivation to this dissertation. **This research proposes a standardised framework (including the information model and the workflow) that is designed to facilitate the reuse of information within the SDL, with a particular focus on 3D LA.** It includes the information model and is designed in alignment with the ISO19152 standard, while it contributes to the standard's revision process.

This concerns development of original knowledge, as current studies have not sufficiently explored how to streamline these processes in a way that enhances efficiency, improves interoperability and facilitates the integration of spatial data across various stages of development. By creating a robust framework capable of managing and leveraging 3D data effectively, this dissertation aims to contribute to the field of (3D) LA in support to SDL. It seeks to pave the way for more sophisticated and practical applications in managing land-related information, thereby enhancing the usability, and accessibility of land administration systems.

In conclusion, the transition towards 3D Land Administration represents a transformative shift in how rights, restrictions and responsibilities, as well as the respective sources can be conceptualised and managed. It is apparent that 3D LAS, in its broader context, is a quite inter-disciplinary field involving experts and knowledge regarding legal aspects (e.g., how to define and register a 3D parcel), institutional support to establish relationships between involved parties, and technical support to realise it (data acquisition methods, modelling, storage and visualisation techniques). In this respect, organisations responsible for LA around the world recognise the need to advance the current practices of property registration by adopting technological drivers and are taking steps forward to register multi-level property rights in such a way that the registration provides insights into the (3D) legal situation (Shnaidman et al., 2018). However, the level of sophistication of each 3D LAS in a jurisdiction will always be based on the user needs, land market requirements, the legal aspects related to the jurisdiction, strategic and planning policies, as well as technological innovations.

Stoter (2004) provided a foundational framework for research on 3D cadastre, identifying the needs, constraints, and possibilities for 3D cadastral registration. In this scene, 3D cadastre is defined as a system that registers and provides insight into rights and restrictions not only on parcels but also on 3D property units. The three pillars are interconnected in a hierarchical order as follows:

- **Juridical aspects.** This pillar investigates how the legal status of stratified properties can be established, how property boundaries beyond traditional 2D parcel boundaries can be established, and what rights can be utilised and how they can be applied.
- **Cadastral aspects.** This aspect addresses how to register the rights and restrictions to property bounded in 3D in the cadastral registration, and how to provide information on the legal status of 3D property situations.
- **Technical aspects.** This pillar explores the system architecture that is needed to support cadastral registration in 3D situations and what is technologically feasible (back into the time of this dissertation – 2004).

Similarly, Aien et al. (2011) underlined the three main aspects of 3D cadastre (Figure 1.2): legal (supporting the register of 3D properties), institutional (establishing relationships and regulations between involved parties), and technical (providing tools and platforms to realise 3D cadastre).

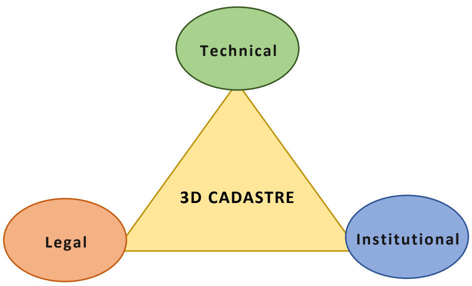

FIG. 1.2 The three main aspects of 3D cadastre (adopted by Aien et al., 2011)

1.2 Research Questions, Research Methodology and terminology

The term **'3D Land Administration'** is preferred over **'3D Cadastres'** due to its broader and less ambiguous implications. In some regions, 'Cadastres' is narrowly interpreted to emphasise only spatial or geographical aspects. In contrast, 'Land Administration' encompasses a more comprehensive approach, integrating legal, administrative, and spatial elements. This dual focus is encapsulated in the concepts of the Land Registry and Legal and Tax Cadastre, providing a clearer and more effective basis for understanding and managing the multifaceted nature of land relationships.

This dissertation advocates '3D Land Administration' over '3D Cadastres'. The latter term has been historically used by the International Federation of Surveyors (FIG) across a series of workshops organised by the "*Joint FIG Commission 3 and 7 Working Group on 3D Cadastres*" since 2001, with key overviews published by FIG (2018b) and van Oosterom (2019). The term '3D Land Administration' reflects the broader context used by the International Standards Organisation (ISO) in ISO 19152:2012, Geographic Information–Land Administration Domain Model (LADM). According to ISO 19152:2012 and ISO 19152-1:2024 (Part 1 of Edition II), LA is defined as "*the process of determining, recording, and disseminating information about the relationship between people and land.*" This definition aligns with the description outlined in the guidelines issued by the United Nations Economic Commission for Europe (UNECE) in 1996.

The two central themes, 3D LA and SDL, form the core of this dissertation, around which, the research questions have been formulated. The broad scope of them is bounded by the LADM revision within ISO and specifically the developments related to LADM Part 2 – Land Registration and some parts of Part 6 – Implementation.

Building on the context described above, the main research question (RQ) of this thesis is:

How to design, develop and evaluate efficient 3D Land Administration in support of the Spatial Development Lifecycle?

The following sub-questions are posed to investigate different aspects of the main question:

1. [Sub-RQ1] – What is the current state-of-the-art in 2D and 3D Land Administration worldwide as: **a)** documented by global reports and reported by countries and **b)** progressed by standardisation organisations?
2. [Sub-RQ2] – Which standards can support data reuse in the context of SDL, particularly in the context of 3D Land Administration?
3. [Sub-RQ3] – **a)** What are the main types of 3D spatial units based on the complexity of their geometry and **b)** how can they be described in a standardised way?
4. [Sub-RQ4] – **a)** Which are the cadastral surveying requirements? **b)** Based on these, how can the survey model for LADM Part 2- Land Registration be developed?
5. [Sub-RQ5] – How can a generic, reference LA workflow be designed, built upon the survey model for LADM Part 2- Land Registration?
6. [Sub-RQ6] – What steps should a country follow to develop a LADM-based country profile?
7. [Sub-RQ7] - How can the applicability and functionality of the survey model for LADM Part 2- Land Registration be validated **a)** at conceptual level; **b)** at a 3D web-based platform and **c)** how the applicability of the reference cadastral survey workflow can be validated?

To address those questions, the research is conducted using Design Science Research (DSR) approach (Hevner and Chatterjee 2010). DSR offers a compelling approach to bridge the relevance gap that has often impeded academic research, centred on addressing critical unresolved issues through innovative methods, as well as enhancing the effectiveness and efficiency of existing solutions.

DSR is not only about crafting new tools or systems but also refining the methods used to build these innovations, ensuring they are both practical and effective (Simon, 1996). This methodology involves a systematic process of identifying problems, designing solutions, and evaluating the effectiveness of these solutions in practical settings, by combining qualitative and quantitative approaches. DSR is structured around three (3) circles:

1. **The Relevance Cycle.** This cycle links the research with the relevant real-world context, ensuring that the research remains closely aligned with real-world applications and needs. It helps to ground the research in practical relevance, guiding both the development of artefacts as well as solutions that address specific problems and demands of end-users or stakeholders.

2. **The Design Cycle.** Central to the iterative nature of design science, this cycle involves a continuous iteration between building, testing and evaluating the design artefacts and processes of the research. This iterative process is central to the refinement of research outputs, facilitating a process where artefacts are not only constructed based on current understanding and technology, but also rigorously tested to ensure they meet specified requirements.

3. **The Rigor Cycle.** This cycle connects the design science activities back to the existing knowledge base. This cycle ensures that the research is informed by and contributes to theoretical foundations, leveraging previous research findings, methodologies, and experiences. The rigor cycle is essential for enhancing the scientific credibility and methodological soundness of the research outcomes, as new knowledge is extracted.

Together, these cycles form a robust foundation which ensures that DSR is relevant, innovative, and rigorously grounded in scientific principles and addresses pertinent challenges. DSR consists of the following six steps (Peffers et al., 2007):

1. Problem identification and motivation
2. Definition of the objectives for a solution
3. Design and development
4. Demonstration
5. Evaluation
6. Communication

In this PhD research DSR methodology is followed. This approach combines both qualitative and quantitative methods to develop a new artefact, *an information model for cadastral surveying, that incorporates both (2D and 3D) professional and crowdsourcing survey techniques and aligns with international standards.*

The first step of the research methodology (*step 1*) followed in this dissertation consists of defining the problem through a comprehensive literature review to create a firm foundation for advancing knowledge and facilitating theory development (Webster & Watson, 2002). This step addresses sub-RQ1a&b, sub-RQ2, sub-RQ3a and sub-RQ4b (the second step). By collecting and synthesing previous research, the objectives of the solutions are formulated (*step 2*).

The next step (*3*) refers to the design and development phase, which includes the design of 3D spatial profiles (relating to sub-RQ3b), the development of a survey model (relating to sub-RQ4b), the design of a reference, cadastral workflow (relating to sub-RQ5), as well as the proposal of a methodological framework to develop LADM-based country profiles (relating to sub-RQ6). All these components of the design phase are aligned with the LADM Edition II developments. For those, requirements' analysis and Action Design Research (ADR) were carried out, incorporating both qualitative and quantitative research. In sub-section 6.1 the activities performed are described in detail (see also Figure 6.1).

The fourth and fifth step of the methodology can be viewed as a validation of the research findings, including: the design of instance level diagrams for the conceptual model of the survey model; the cadastral workflow demonstration in three countries; experts' consultation through the ISO TC 211 revision process of LADM and the development of 3D LAS web-based prototype implementation (related to sub-RQ7a,b&c). Finally (*step 6*), research findings are communicated through conferences, workshop papers, journal articles, and presentations. Discussions are also held within ISO TC 211 and OGC, also addressing sub-RQ7a.

The following figure illustrates the research methodology followed in this dissertation.

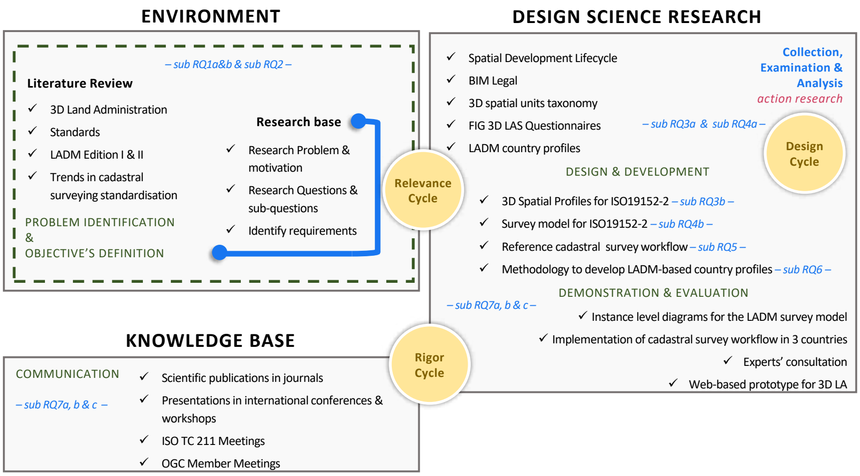

FIG. 1.3 Research methodology followed in the PhD dissertation (Hevner and Chatterjee, 2010; adapted)

1.3 Research setup

This section outlines the structure and setup of the PhD research, highlighting the various related activities that were executed in parallel with the research and their interrelationships within the context of the PhD journey. These activities are not isolated academic tasks; rather, they encompass practical projects in industry, collaborative research initiatives (including those funded by European grants), and involvement in standardisation activities among international standardisation bodies, such as ISO TC211 and OGC.

Each of these parallel activities contribute uniquely to the holistic development of the research, namely:

- This research has been conducted under the framework of the **H2020 project Galileo Improved Services for Cadastral Augmentation Development On-field Validation (GISCAD-OV[2]), under Grant Agreement No. 870231**. Spanning from January 2020 to May 2023, it has been integrally linked with cutting-edge developments in the design, development, and validation of a cost-effective Galileo High Accuracy Service for cadastral surveying. This service leverages the capabilities of GPS+Galileo High Accuracy Services (HAS) and Precise Point Positioning-Ambiguity Resolution (PPP-AR) (Glaner et al., 2021) quick convergence techniques. The research from this project contributes to this PhD research through the following three aspects:

  a. One task of the project was devoted to the development and distribution of a **questionnaire to National Mapping Cadastral Authorities (NMCAs)** across seven countries that participated in the pilot studies of the project (Estonia, Spain, Germany - North Rhine-Westphalia, France, Croatia, Czech Republic and Italy), facilitated by the Council of European Geodetic Surveyors (CLGE). The questionnaire focused on the Global Navigation Satellite System (GNSS) services provided by each country and the standards adopted in cadastral and mapping processes. By integrating questions that probed the use of international standards (such as ISO19152:2012) data submission formats (i.e. GeoJSON, CityGML, LandXML, etc.) and data modelling specifications, this research offers a comprehensive assessment of the implementation and potential gaps in these standards.

2 https://giscad-ov.eu

TOC

b. Second, these technologies represent significant progress in the precision and efficiency of spatial data acquisition, aligning well with one of the main objectives of this PhD research, to standardise cadastral surveying modelling and workflows. Through this alignment, the research not only contributes to the theoretical knowledge but also provides **practical, validated solutions** to enhance LASs globally.

c. Finally, the research leverages real-world data from **pilot campaigns** of the project conducted in Olpe, Germany and Tallinn, Estonia to validate the proposed developments of the GISCAD-OV project and simultaneously, the developments adopted in ISO 19152-2:2025- Land Registration. The real-world data include a BIM model and the results of a cadastral survey. This validation process not only provided valuable practical experience with the project's proposed technology, but also demonstrated the applicability and robustness of the refined survey model through real-world cases, improvements, ensuring that the advancements are both theoretically sound and practically viable.

- Moreover, the research is closely associated and conducted in parallel with the **revision of ISO19152:2012 Land Administration Domain Model** carried out within ISO TC211 *Geographic Information/ Geomatics* WG7 *Information Communities*. In this context, part of this research has been presented and discussed during ISO TC 211 meetings, as well as during Member Meetings of the Open Geospatial Consortium (OGC).

It is important to note that in this dissertation, **the term "LADM Edition II"** is used to refer to the second edition of the ISO 19152 LADM standard, following ISO 19152:2012. However, ISO follows a different naming convention, where each LADM Part introduced for the first time is officially referred to as the first edition of that specific part.

Figure 1.4 presents the timeline of this thesis and the core projects and standardisation activities that closely relate to this and run in parallel.

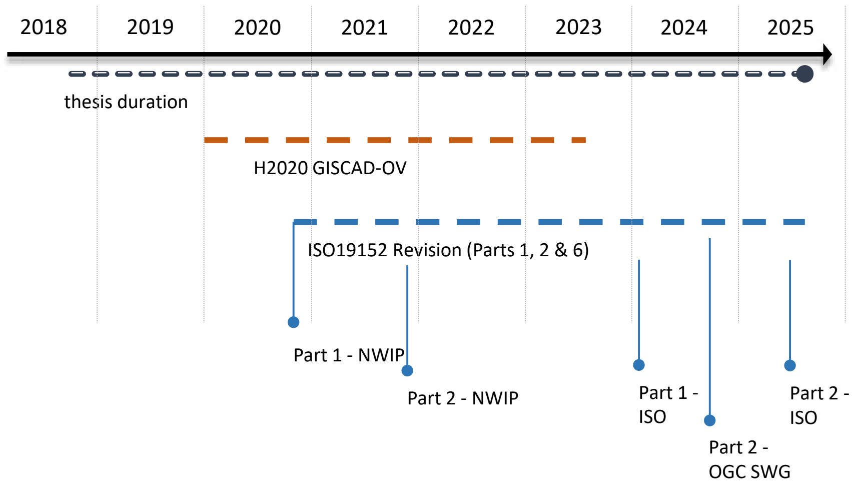

FIG. 1.4 Timeline of core projects and standardisation activities that closely relate to this thesis

1.4 Main contributions of the dissertation and research topics beyond its scope

This section reflects on the main findings of this research, grouped into the two main pillars that provides contribution –3D LA and SDL:

– The main contributions of this dissertation in the field of **3D LA and LADM** are the following:

  a The development of standardised 3D Spatial profiles, which are adopted in ISO 19152-2:2025. Spatial profiles can efficiently support a holistic lifecycle thinking and enhance the interoperability between the different phases and disciplines. (Kalogianni et al., 2020b). This contribution relates to *sub-RQ3b*.

TOC

b. The development of a standardised information model for cadastral surveying. This model is adopted by ISO19152-2:2025. The first Edition of the LADM refers to ISO 19156:2011 Observations and Measurements (ISO, 2011), in a very generic form and therefore, a refined model for more specific survey techniques, which addresses survey related aspects is required.
This contribution relates to *sub-RQ4b*.

c. The development of a standards' based generic workflow describing cadastral surveying, including both professional and crowdsourcing data acquisition techniques. The workflow covers both text-based, 2D and 3D data and is built on the experience from several countries This contribution relates to *sub-RQ5* and contributes to the development of ISO19152-6: Implementation.

d. The development of a methodology to create LADM-based country profiles based on distilling good practice and collective experience from several country profiles. This approach contributes to the development of ISO19152-6: Implementation. This relates to *sub-RQ6*.

e. The development of a web-based 3D Land Administration prototype (as proof of feasibility and feedback loop, for possible further improvement) using both survey and design sources. This development relates to *sub-RQ7b*.

- The core contributions of this dissertation in the field of **standardisation and SDL** are the following:

  - The introduction of the concept of reusing information across different phases of the SDL for 3D LA as a move towards data circularity. In this scene, new data sources and technologies to support (2D and 3D) cadastral survey procedures are introduced.

To ***delineate the thematic bounds*** of this research, the following list presents research topics that are relevant to the context of this study but are not investigated within its scope.
These topics acknowledge the broader context without providing new insights:

- Topics related to the full spectrum of 3D LA aspects, LADM Edition II and operationalisation of LAS:

TOC

a. *Legal, juridical and organisational pillars:* While such aspects of LA will be merely used as preconditions in this thesis, it is not the aim of the dissertation to analyse them. In this respect, the topics of overlapping real property rights and Public Law Restrictions (PLRs) are outside of its scope.

b. *Operational 3D LAS:* The development and implementation of fully operational 3D cadastral registration systems are not addressed. This research focuses on foundational information models and workflows rather than the complete system deployment.

c. *Crowdsourcing in 3D cadastral surveys:* The development of a method to assess the accuracy of crowdsourced data based on a range of methods and technologies, based on the cadastral survey generic workflow (section 6.4), is not explored in this research.

d. *Performance Measurement and Benchmarking:* Measuring performance and benchmarking 3D LAS, with comparison between different countries, falls outside the purview of this research.

e. *LADM Edition II:* The development of components for the other Parts of ISO 19152 LADM Edition II and specifically, Part 3: Marine Georegulation, Part 4: Valuation Information and Part 5: Spatial Plan Information, goes beyond the scope of this research.

– Topics related to the **SDL**:

a. *All information flows within the SDL:* Information flows between the other phases of the SDL (planning, permitting, designing, financing, construction, etc.) are not considered within the scope of this research and are not investigated. The focus remains on LA.

b. *Circular built environment:* aspects related to circularity in materials and building components, construction, waste mapping and management and resource flows are beyond the scope.

By outlining these topics, the dissertation maintains a clear focus on its core contributions while recognizing the broader context and potential areas for future research.

1.5 Outline of the dissertation

The dissertation is organised into 3 Parts consisting of 9 chapters, as illustrated in Figure 1.5. Part of the thesis is based on journal and conference papers that have been published during this PhD research. An overview of those journal and conference papers is presented in section 1.6. Each chapter starts with a brief preamble that explains its relation to the research questions and consolidate the main findings into a summary/ discussion. This approach ensures that readers can easily understand how each component of the study contributes to the broader research objectives and allows for a cohesive integration of findings across the dissertation.

Chapter 1 – Introduction sets the stage for the research by presenting an overview of the topic under investigation, articulating the driving motivation behind the research and outlining the research questions and methodology. In this part, the main research focus and research contributions and boundaries are presented, providing a comprehensive foundation for the following parts and chapters.

PART I – Related Work & Background consists of 3 chapters and presents in detail the research context and the relevant background knowledge.

Chapter 2 – Land Administration presents the main aspects and the context of 3D LA. The chapter reviews relevant research on global initiatives that encompass a variety of parameters aimed at improving 3D LASs. These initiatives highlight the critical need for sustainable and efficient management of space, considering both two-dimensional and three-dimensional aspects of LA. To conclude the state-of-the-art in LA, chapter 2 presents an inventory of the status of 3D Land Administration Systems worldwide as of the end of 2022. This information is based on the survey conducted by the FIG Working Group 7.3 “3D and LADM (3D/LADM)”[3], in 2022, which gathered insights from countries around the world.

Chapter 3 – State of the Art in Standardisation of (Geo) Information Management for the Built Environment delves into the crucial role of standardisation in the management of geospatial information, specifically within the built environment. The chapter thoroughly reviews the current state of standards and their development, focusing on ensuring data circularity throughout the Spatial Development Lifecycle and particularly in LA. It highlights key international standards such as IFC, and

3 https://fig.net/organisation/comm/7/workplan_23-26.asp#7.3

LandInfra, illustrating how these have evolved to foster data interoperability and reuse across various stages of the SDL. Special emphasis is placed on the Australian/New Zealand Cadastral Survey Data Model, which incorporates survey and design data, underscoring its role in aligning geospatial standards to streamline LA processes and enhance the effectiveness of data exchange within the built environment.

Chapter 4 – The Land Administration Domain Model [LADM] presents the ISO1952:2012, its main concepts and classes and its support for 3D functionality. Additionally, it introduces the Social Tenure Domain Model (STDM), a specialisation of LADM and outlines the revision of the standard, which has been organised in accordance with ISO regulations. The primary objective of LADM Edition II is to enrich the context of the first edition and broaden its scope in response to feedback and requests from the global LA community. Therefore, the developments towards this revision are presented, tracking the progress and implementations of LADM since its designation as an ISO standard in 2012 until the commencement of its revision process in 2020. Additionally, it includes updates on the parts of Edition II that have achieved International Standard (IS) status (all Parts from 1-5, except from Part 6), offering a comprehensive view of the evolution and impact of LADM within the field of LA.

The chapter also features an inventory of LADM-based country profiles from various regions worldwide. This inventory not only showcases the extensive adoption and adaptability of the LADM but also serves as a valuable resource for countries and researchers seeking to establish or enhance their own LAS. Moreover, the inventory serves as a repository of knowledge for researchers and practitioners interested in understanding the global landscape of LA and the role of standardised models like LADM in facilitating efficient and effective management of land resources.

PART II – 3d Spatial Units and Sources consists of 2 chapters and focuses on analysing and modelling the concepts presents in the first Part of the dissertation.

Chapter 5 – The Spatial Development Lifecycle introduces the concept of the SDL, detailing its characteristics, emphasising the importance of adopting a data circularity approach within the built environment. The chapter presents an inventory of generic use cases that have driven the categorisation of 3D spatial units into distinct groups sharing similar characteristics, presenting a revised taxonomy of spatial units. The chapter then delves into the various data sources for these (3D) spatial units for LA, categorising them into two principal groups for a detailed analysis. The sources from data survey methods and the sources from the design phase, with the introduction of BIM Legal concept.

Chapter 6 – 3D LA Modelling Iin Support to the Spatial Development Lifecycle is one of the core contributions of this research, presenting the modelling of the concepts previously discussed throughout the thesis. The innovative models presented in this chapter have been adopted by Parts 2 (ISO19152-2:2025) and contribute to Part 6. Following an analysis of the modelling approach followed in this chapter, it introduces the 3D spatial profiles, which are included in Annex C (informative) '2D and 3D Representation of Spatial Units' of ISO19152-2:2025 (ISO, 2025a). This inclusion marks an acknowledgment of the need for standardising the representation of spatial units in both 2D and 3D enhancing clarity and interoperability in LA practices. Furthermore, the refined survey model, developed as part of this research and incorporated into ISO19152-2;2025 is presented. In addition to these contributions, the generic, reference cadastral survey workflow -developed within this dissertation and expected to contribute to the (under development) ISO 19152-6, is analysed. This workflow provides a standardised approach to cadastral surveying that is adaptable to a variety of jurisdictions and technological contexts, facilitating better practices in cadastral surveying.

PART III – Development and Evaluation is structured into two chapters, along with the concluding chapter of this dissertation. **Chapter 7 – Developing LADM Methodology: Insights from 3D LA and LADM International**, initiates with a thorough analysis of global perspectives on 3D LAS about future trends as reported by various countries, highlighting both successes and areas for improvement. Building on the inventory of LADM country profiles presented in Part I of the thesis, this chapter outlines the criteria and characteristics used to identify good practices within these profiles. A quantitative comparative analysis is then conducted to measure and evaluate them. This analysis not only highlights the strengths of current implementations but also identifies key trends and patterns that can inform future developments. The insights gained from this comparative analysis lead directly to the development of a methodology for creating LADM-based country profiles.

Chapter 8 – Validation of the Proposed Developments focuses on the validation of the developments. The validation process is structured into two main parts to comprehensively assess the effectiveness and practicality of the new methodologies and models. The first part is conceptual and involves the design of instance level diagrams for the LADM survey model for two specific use cases. This conceptual validation helps to refine the theoretical underpinnings of the survey model, ensuring that it is both accurate and applicable to real-world situations. The same applies with the reference cadastral survey workflow, that is applied into three countries to be validated, while allowing for a feedback loop for further improvement, if and where needed.

The second part of the validation process involves the development of a 3D web-based prototype that utilises BIM files for 3D LA. Following the development, the prototype undergoes evaluation to assess its effectiveness using real-world IFC models (http://159.223.219.149/).

Finally, **Chapter 9 – Conclusions and Future Research**, encapsulates the insights and findings from the research, effectively concluding the study with a synthesis of key takeaways and comprehensive answers to the research questions. It highlights the main contributions of the research, underlining how these advances have filled existing gaps and have extended the knowledge base of 3D LA. A personal reflection follows. The thesis concludes with proposals for future research and developments, suggesting directions for upcoming research that can build on the findings and contributions of this study.

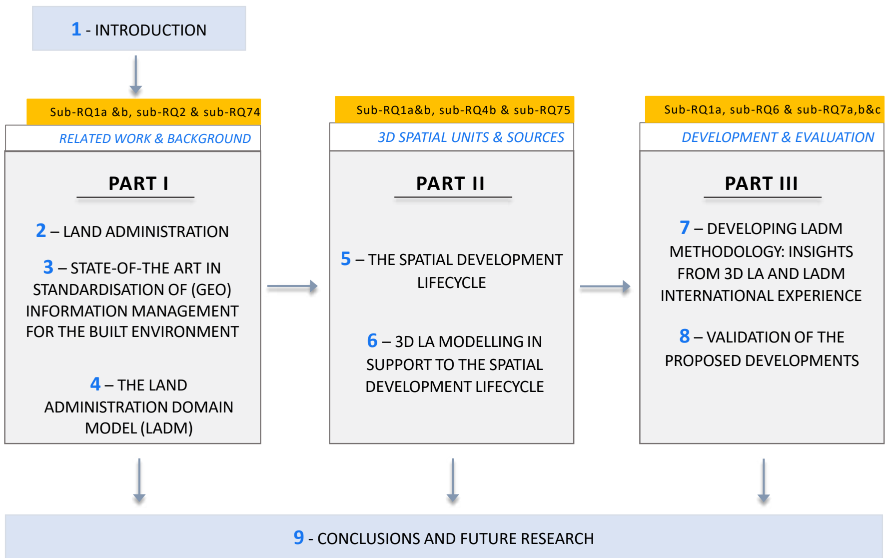

FIG. 1.5 The outline of this dissertation

1.6 List of publications

At this section, all the publications that have been published during the PhD research and are presented. Those which are relevant to specific the chapters of the dissertation are linked to the respective ones.

INTERNATIONAL SCIENTIFIC JOURNAL ARTICLES		
#	PUBLICATION	CHAPTER
1	**Kalogianni, E**., Dimopoulou, E., Gruler, H.C., Stubkjær, E., Morales, J., Lemmen, C.H.J., van Oosterom, P.J.M. (2024). Refining the survey model of the LADM ISO 19152–2: Land registration. *Land Use Policy*, 141, 107125. doi: https://doi.org/10.1016/j.landusepol.2024.107125	6 & 8
2	**Kalogianni, E.**, Janečka, K., Kalantari, M., Dimopoulou, E., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., Govedarica, M., Lemmen, C.H.J., van Oosterom, P.J.M. (2021). Methodology for the development of LADM country profiles. *Land Use Policy*, 105, 105380. doi: https://doi.org/10.1016/j.landusepol.2021.105380	4 & 7
3	**Kalogianni, E.**, Dimopoulou, E., Thompson, R.J., Ying, S., van Oosterom, P.J.M. (2020). Development of 3D spatial profiles to support the full lifecycle of 3D objects. *Land Use Policy*, 98, 104177. doi: https://doi.org/10.1016/j.landusepol.2019.104177	5 & 6
4	**Kalogianni, E.**, van Oosterom, P.J.M., Dimopoulou, E., Lemmen, C.H.J. (2020). 3D land administration: A review and a future vision in the context of the spatial development lifecycle. *ISPRS international journal of Geo-Information*, *9*(2), 107. doi: https://doi.org/10.3390/ijgi9020107	2
5	Batum, S., **Kalogianni, E.**, van Oosterom, P.J.M. (2025). Spatial Plan Registration and Compliance Checks in Estonia, based on LADM Part 5: Spatial Plan Information". (DOI - 10.1080/00396265.2025.2547462, *Survey Review)*	5
6	Kara, A., Lemmen, C.H.J., Oosterom, P.J.M., **Kalogianni, E.**, Alattas, A., Indrajit, A. (2024). Design of the new structure and capabilities of LADM Edition II including 3D aspects. *Land Use Policy*, 137, 107003. doi: https://doi.org/10.1016/j.landusepol.2023.107003	4
7	Chen, M., van Oosterom, P.J.M., **Kalogianni, E**., Dijkstra, P., Lemmen, C.H.J. (2024). Bridging Sustainable Development Goals and Land Administration: The Role of the ISO 19152 Land Administration Domain Model in SDG Indicator Formalization. *Land*, 13(4), 491. doi: https://doi.org/10.3390/land13040491	2
8	Broekhuizen, M., **Kalogianni, E.**, van Oosterom, P.J.M. (2025). BIM/IFC as input for registering apartment rights in a 3D Land Administration Systems - A Prototype Webservice. *Land Use Policy*, 148. doi: https://doi.org/10.1016/j.landusepol.2024.107368	5
9	Ramlakhan, R., **Kalogianni, E.**, van Oosterom, P.J.M., Atazadeh, B. (2023). Modelling the legal spaces of 3D underground objects in 3D land administration systems. *Land Use Policy*, 127, 106537. doi: https://doi.org/10.1016/j.landusepol.2023.106537	-
10	Kitsakis, D., **Kalogianni, E.**, Dimopoulou, E. (2022). Public Law Restrictions in the Context of 3D Land Administration—Review on Legal and Technical Approaches. *Land*, 11(1), 88. doi: https://doi.org/10.3390/land11010088	2
11	Polat, Z.A., Alkan, M., Paulsson, J., Paasch, J.M., **Kalogianni, E.** (2022). Global scientific production on LADM-based research: A bibliometric analysis from 2012 to 2020. *Land Use Policy*, 2022, 112, 105847. doi: https://doi.org/10.1016/j.landusepol.2021.105847	-
12	Alattas, A., **Kalogianni, E.**, Alzahrani, T., Zlatanova, S., van Oosterom, P.J.M. (2021). Mapping private, common, and exclusive common spaces in buildings from BIM/IFC to LADM. A case study from Saudi Arabia. *Land Use Policy*, 104, 105355. doi: https://doi.org/10.1016/j.landusepol.2021.105355	-

INTERNATIONAL CONFERENCE PROCEEDINGS		
#	PUBLICATION	CHAPTER
13	**Kalogianni, E.,** van Oosterom, P.J.M., Lemmen, C.H.J., Ploeger, H., Thompson, R.J., Karki, S., Shnaidman, Rahman, A.A. (2023). 3D Land Administration: Current Status (2022) and Expectation for the Near Future (2026) – Initial Analysis. In Proceedings: *FIG Working Week 2023*.	2 & 7
14	**Kalogianni, E.,** van Oosterom, P.J.M., Schmitz, M., Capua, R., Verbree, E., Dimopoulou, E., Gruler, H.C., Stubkjær, E., Neudiens, I., Morales, J., Lemmen, C.H.J. (2023). Galileo High Accuracy Services support through ISO 19152 LADM Edition II. In Proceedings: *FIG WW 2023*., part of ISBN: 978-87-93914-07-0	8
15	**Kalogianni, E.,** van Oosterom, P.J.M., Lemmen, C.H.J., Thompson, R.J., Karki, S., Shnaidman, A., Abdul Rahman, A. (2023). 3D Land Administration: Current Status (2022) and Expectation for the Near Future (2026). In Proceedings: *FIG WW 2023*, part of ISBN: 978-87-93914-07-0	-
16	**Kalogianni, E.**, Gruler, H.C., Bar-Maor, A., Harold, B., Lemmon, T., Lemmen, C.H.J., van Oosterom, P.J.M. (2022). Investigating the Requirements for the ISO 19152 LADM Survey Encodings. In Proceedings: *10th International FIG Workshop on the Land Administration Domain Model*, pp. 53-66, doi: https://doi.org/10.4233/uuid:a604a23a-5658-4c4f-a052-20980fcd4554	5
17	**Kalogianni, E.**, Kara, A., Beck, A., Paasch, J.M., Zevenbergen, J., Dimopoulou, E., Kitsakis, D., van Oosterom, P.J.M., Lemmen C.H.J. (2022). Refining legal Land Administration-related aspects in LADM. In Proceedings: *10th International FIG Workshop on the Land Administration Domain Model*, pp. 255-276, doi: https://doi.org/10.4233/uuid:1dcccbbd-bcc3-42df-9a55-b29817b0665e	-
18	**Kalogianni, E.**, Dimopoulou, E., Gruler, H.C., Stubkjær, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2021b). Developing the refined survey model for the LADM revision supporting interoperability with LandInfra. In Proceedings: *FIG Working Week 2021*, pp. 27, part of ISBN: 978-87-92853-65-3	3 & 8
19	**Kalogianni, E.**, Dimopoulou, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2020). BIM/IFC files for 3D real property registration: an initial analysis. In Proceedings: *FIG Working Week 2020*, pp. 1-22, part of ISBN: 978-87-92853-93-6	3 & 5
20	**Kalogianni, E.**, Kalantari, M., Dimopoulou, E., van Oosterom, P.J.M. (2019). LADM country profiles development: Aspects to be reflected and considered. In Proceedings: *8th FIG Land Administration Domain Model Workshop 2019*, pp. 287-302, part of ISBN: 9788792853929.	-
21	**Kalogianni, E.**, Dimopoulou, E., van Oosterom, P.J.M. (2018), 3D Cadastre and LADM - Needs and Expectations towards LADM Revision, In Proceedings: *7th Land Administration Domain Model Workshop 2018*, pp. 67-88, part of ISBN: 978-87-92853-69-1	-
22	**Kalogianni, E.**, Dimopoulou, E., Thompson, R.J., Lemmen, C.H.J., van Oosterom, P.J.M. (2018). Investigating 3D spatial units as basis for refined 3D spatial profiles in the context of LADM revision. In Proceedings: *6th International Workshop on 3D Cadastres*, pp. 177-199, part of ISBN: 978-87-92853-81-3	5
23	Batum, S., **Kalogianni, E.**, Broekhuizen, M., Raitviir, Ch., Mägi, K., van Oosterom, P.J.M. (2024). Leveraging BIM/IFC for the Registration of Spatial Plans and Compliance Checks and Permitting in Estonia based on LADM Part 5 - Spatial Plan Information. In Proceedings: *6th International Workshop on 3D Cadastres*, pp. 177-199, part of ISBN: 978-87-92853-81-3	-
24	Poulaki, M., Xagoraris, N., **Kalogianni, E.**, Kyriakidis, Ch., Kara, A., Dimopoulou, E. (2024). Developing a LADM Part 5 – Spatial Plan Information country profile for Greece. In Proceedings: *12th International FIG Land Administration Domain Model & 3D Land Administration Workshop*, part of ISBN: 978-87-93914-17-9.	-
25	Thompson, R.J., **Kalogianni, E.,** van Oosterom, P.J.M. (2023). Analysing 3D Land Administration developments and plans from 2010 to 2026. In Proceedings: *11th International FIG Workshop on LADM/3D LA*, pp. 119-132, part of ISBN: 978-87-93914-09-4, doi: https://doi.org/10.4233/uuid:b02e4370-e0d9-40dd-90d1-bbbd647505f1	2

>>>

INTERNATIONAL CONFERENCE PROCEEDINGS		
#	PUBLICATION	CHAPTER
26	Kara, A., Lemmen, C.H.J., **Kalogianni, E.** van Oosterom, P.J.M. (2023). Requirements Based Design of the LADM Edition II. In Proceedings: *11th International FIG Workshop on LADM/3D LA*, pp. 181-194, part of ISBN: 978-87-93914-09-4, doi: https://doi.org/10.4233/uuid:8843a8e1-09b0-4b44-afaf-73b391e26e8e.	-
27	Chen, M., van Oosterom, P.J.M., **Kalogianni, E.,** Dijkstra, P. (2023). SDG Land Administration Indicators based on ISO 19152 LADM. In Proceedings: *11th International FIG Workshop on LADM/3D LA*, pp. 77-92, part of ISBN: 978-87-93914-09-4, doi: https://doi.org/10.4233/uuid:aa432673-6150-4665-aae9-eb708cfc8a86	-
28	Demetriades, P., **Kalogianni, E.,** Dimopoulou, E. (2023) Leveraging BIM for the LADM Part 4 - Valuation Information Model: the case study of Cyprus. In Proceedings: *11th International FIG Workshop on LADM/3D LA*, part of ISBN: 978-87-93914-09-4	-
29	Lemmen, C.H.J., van Oosterom, P.J.M., Kara, A., **Kalogianni, E.,** Alattas, A., Indrajit, A., (2023). Overview of Developments of Edition II of the Land Administra tion Domain Model. In Proceedings: *FIG WW 2023.*, part of ISBN: 978-87-93914-07-0	-
30	Guler, D., Alattas, A., Broekhuizen, M., **Kalogianni, E.,** Kara, A., Oosterom, P.J.M. (2022). 3D Registration of Apartment Rights Using BIM/IFC: Comparing the Cases of the Netherlands, Saudi Arabia, and Turkey. In Proceedings: *XXVII FIG Congress 2022*, pp.1-21.	-
31	Broekhuizen, M., **Kalogianni, E.**, van Oosterom, P.J.M. (2021). BIM Models as Input for 3D Land Administration Systems for apartment registration. In Proceedings: *7th International Workshop on FIG 3D Cadastre*, pp. 53-74, doi: https://doi.org/10.4233/uuid:5e240a06-5fdf-4354-9e6d-09c675f1cd8b	-
32	Ramlakhan, R., **Kalogianni, E.**, van Oosterom, P.J.M. (2021). Modelling 3D underground objects in 3D Land Administration Systems. In Proceedings: *7th International Workshop on FIG 3D Cadastre*, pp. 37-52, doi: https://doi.org/10.4233/uuid:4a499efb-f348-456b-9965-65c47519337a	-
33	Kitsakis, D., **Kalogianni, E.**, Dimopoulou, E., Zevenbergen, J., van Oosterom, P.J.M. (2021). Modelling 3D legal spaces of Public Law Restrictions within the context of LADM revision. In Proceedings: *7th International Workshop on FIG 3D Cadastre*, pp. 371-390, doi: https://doi.org/10.4233/uuid:a116493a-2cb6-4781-b2c4-3f2c94611ad8	-
34	Lemmen, C.H.J., Alattas, A., Indrajit, A., **Kalogianni, E.**, Kara, A., Oukes, P., van Oosterom, P.J.M. (2021). The Foundation of Edition II of the Land Administration Domain Model. In Proceedings: *FIG Working Week 2021*, pp.17, part of ISBN: 978-87-92853-65-3	-
35	Lemmen, C.H.J., van Oosterom, P.J.M., Unger, E.M., **Kalogianni, E.**, Shnaidman, A., Kara, A., Alattas, A., Indrajit, A., Smyth, K., Milledrogues, A., Bennett, R., Oukes, P., Gruler, H.C., Casalprim, D., Alvarez, G., Aditya, T., Sucaya, K.G.A., Morales, J., Balas, M., Zulkifli, N.A., de Zeeuw, C. (2020). The land administration domain model: advancement and implementation, In Proceedings: *Annual World Bank Conference on Land and Poverty 2020*, pp. 1-28.	-
36	Lemmen, C.H.J., van Oosterom, P.J.M., Kara, A., **Kalogianni, E.**, Shnaidman, A., Indrajit, A., Alattas, A. (2019). The scope of LADM revision is shaping-up. In Proceedings: *8th FIG Land Administration Domain Model Workshop 2019*, pp. 1-36, part of ISBN: 9788792853929.	-
37	van Oosterom, P.J.M., Kara, A., **Kalogianni, E.**, Shnaidman, A., Indrajit, A., Alattas, A., Lemmen, C.H.J. (2019). Joint ISO/TC211 and OGC Revision of the LADM: Valuation Information, Spatial Planning Information, SDG Land Indicators, Refined Survey Model, Links to BIM, Support of LA Processes, Technical Encodings, and Much More on Their Way! In Proceedings: *FIG Working Week 2019*, pp. 25, part of ISBN: 978-87-92853-90-5	-
38	Kalantari, M., **Kalogianni, E.**, (2018). Towards LADM Victoria country profile – modelling the spatial information, In Proceedings: *6th International Workshop on 3D Cadastres*, pp. 483-498, part of ISBN: 978-87-92853-81-3	-

The following two categories list manuscripts that have been accepted and published as reviewed book chapters and/ or other magazines and they do not include any direct reference to the chapters of this dissertation.

PEER-REVIEWED BOOK CHAPTERS (CONFERENCE PAPERS)	
#	PUBLICATION
39	**Kalogianni, E.,** Floros, G.S., Dimopoulou, E. (2021). Investigating transport infrastructure objects within their Spatial Development Lifecycle. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 8(VIII-4/W2-2021), pp. 129–13.
40	**Kitsakis D.,** Kalogianni, E., Dimopoulou, E., van Oosterom, P.J.M. (2018). Requirements for Standardised Representation of Public Law Restrictions based on LADM. In Proceedings: *FIG Commission 3 Workshop and Annual Meeting 2018 - Spatial Information in the Era of Data Science: Challenges and Practical Solutions*.

PROFESSIONAL PUBLICATIONS/ OTHERS	
#	PUBLICATION
41	Lemmen, C.H.J., van Oosterom, P.J.M., Kara, A., **Kalogianni, E.** (2025). The Land Administration Domain Model – An Overview. FIG Publication No 84. International Federation of Surveyors (FIG). ISBN 978-87-93914-23-0.
42	Lemmen, C.H.J., van Oosterom, P.J.M., **Kalogianni, E.** (2020). LADM: The next phase. *GEO: connexion*, 2020, 19(3): 20–21.
43	Lemmen, C.H.J., Chipofya, M., da Silva Mano, A., van Oosterom, P.J.M., Kara, E., **Kalogianni, E.,** Morscher-Unger, E.M., Morales Guarin., J., Beck, A., Huera, D.U., Honer, S., Bennett, R., Dijkstra, P., Zavenbergen, J. (2025). LADM in the classroom. Available online: https://ris.utwente.nl/ws/portalfiles/portal/487283025/LADM_ITC_Book_ext-2025.pdf.

PART I

Related work & background

2 Land Administration

[Sub-RQ1a] **What is the current state-of-the-art in standardisation in (2D and 3D) Land Administration around the world, as documented by global reports and reported by countries?**

This chapter is based on the following publications:
Kalogianni, E., *van Oosterom, P.J.M., Dimopoulou, E., Lemmen, C.H.J. (2020). 3D land administration: A review and a future vision in the context of the spatial development lifecycle. ISPRS international journal of Geo-Information, 9(2), 107.*
Kalogianni, E., *van Oosterom, P.J.M., Lemmen, C.H.J., Ploeger, H., Thompson, R.J., Karki, S., Shnaidman, Rahman, A.A. (2023). 3D Land Administration: Current Status (2022) and Expectation for the Near Future (2026) – Initial Analysis. In Proceedings: FIG Working Week 2023.*
Chen, M., van Oosterom, P.J.M., ***Kalogianni, E.,*** *Dijkstra, P., Lemmen, C.H.J. (2024). Bridging Sustainable Development Goals and Land Administration: The Role of the ISO 19152 Land Administration Domain Model in SDG Indicator Formalization. Land, 13(4), 491.*
Thompson, R.J., ***Kalogianni, E.,*** *van Oosterom, P.J.M. (2023). Analysing 3D Land Administration developments and plans from 2010 to 2026. In Proceedings: 11th International FIG Workshop on LADM/3D LA, pp. 119-132, part of ISBN: 978-87-93914-09-4.*
Kitsakis, D., ***Kalogianni, E.***, *Dimopoulou, E. (2022). Public Law Restrictions in the Context of 3D Land Administration—Review on Legal and Technical Approaches. Land, 11(1), 88.*

ABSTRACT

The practice of recording rights on land and making these records accessible through state-held systems, dates back to ancient Mesopotamian civilizations around 4000 B.C. (Kitsakis, 2019). Over time, LAS have evolved, shaped by legal, organizational, and technical aspects, to meet the ever-changing societal needs, urbanisation, and technological progress. The development of complex, and overlapping 3D spaces both above and below the earth, has introduced new challenges in the registration of complex real-property private-law rights and Public-Law Restrictions (PLRs), both of which are critical for effective LA. Various systems have been developed around the world for the registration of 2D and, in some cases, 3D rights and restrictions, as discussed in section 2.1.
In parallel, the UN Sustainable Development Agenda 2030 and other global strategic frameworks have recognised the multifaceted value of LASs, emphasising their role in supporting social, economic, and environmental objectives. These frameworks have underscored the importance of tracking progress in LAS through the development of specific indicators, which are outlined in section 2.2.
The author, as co-chair of the Joint Working Group 7.3 “3D and LADM (3D/LADM)” of FIG Commission 7 “Land Management and Cadastre” and FIG Commission 3 “Spatial

Information Management” for the term 2023-2026, has been actively involved in the preparation, distribution and analysis of the 4th FIG Questionnaire on 3D Land Administration 2022-2026. This analysis, encompassing responses from 37 countries, has resulted in a comprehensive inventory designed to promote knowledge exchange, share best practices, and support future advancements in 3D land administration, as detailed in section 2.3. The chapter concludes with a summary of the findings.

2.1 3D Land Administration

Land is a fundamental asset that underpins a country’s economy, stability, and sustainability (Chehrehbargh et al., 2024) and must be managed efficiently. Effective LA ensure proper management of land resources, property rights, land use, planning and valuation, all of which are crucial for sustainable development. In this scene, LASs play a key role by determining, recording and disseminating land-related information (UNECE, 1996). This section explores various dimensions of 3D LA are presented. sub-section 2.1.1 focuses on the fundamental aspects and dimensions of people-to-land relationships. Sub-section 2.2.2 outlines the evolution towards 3D LA, and the last sub-section discusses the legal, organisational and technical aspects that underpin 3D LA implementation.

2.1.1 Understanding people-to-land relationships and their administration

People-to-land relationships are documented in a LAS (Figure 2.1), ensuring land tenure security, fostering fairness in land markets and promoting efficient land development. As urbanisation grows, the need for robust LA becomes increasingly critical. LA integrates land parcel-related information into a comprehensive system, supported by defined administrative and technical roles, processes, and enabling technologies. This facilitates the resolution of land disputes, management of transactions, access to credit, land ownership transfer, land valuation, taxation, and informed decision-making regarding land use and development changes (Bennett et al., 2020).

Countries establish Land Administration Systems (LASs) to manage land-related information within broader Spatial Information Infrastructures (SII) (van Loenen, 2006; van Oosterom et al., 2009). LASs form a legally significant link between individual people and between people to land, capturing RRRs. A complete understanding of land-related information must also consider restrictions and responsibilities whether related to land or 3D space (Indrajit et al., 2020). Although no universal definition of LA exists, Dale and McLaughlin (1999), describe it as encompassing all processes related to regulating land and property development, land use conservation and conflict resolutions concerning ownership and use. The Land Administration Guidelines by the United Nations Economic Commission for Europe (UNECE) include a widely accepted definition of LA as: "*the processes of recording and disseminating information about the ownership, value and use of land and* data on ownership, Rights, Restrictions and Responsibilities (RRRs), as well as the surveying and mappings to describe properties spatially.

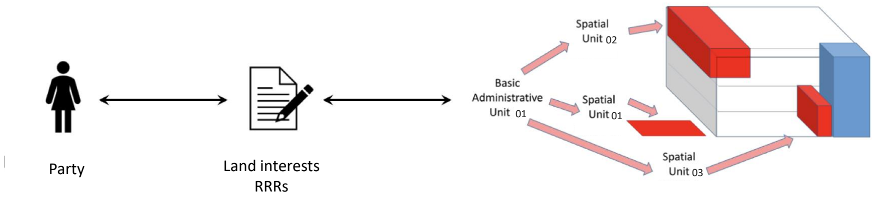

FIG. 2.1 An illustration of people-to-land relationships (Lemmen et al, 2021; adapted)

According to Enemark (2005) and Williamson et al. (2010), LA encompasses a wide range of interconnected systems and processes:

1 **Land Tenure:** This involves the allocation and security of land rights, conducting surveys to determine boundaries of spatial units, transferring rights through sale or lease, as well as managing and resolving disputes over tenure relationships and boundaries.
2 **Land Value:** This function involves assessing land and property value, collecting tax revenue, resolving disputes over valuation and taxation, and managing compensation, expropriation, mortgages, and transaction values.
3 **Land Use:** This involves the regulation of land use through the adoption of planning policies at national, regional, and local levels, enforcing these regulations, and resolving land use conflicts.
4 **Land Development:** This includes constructing infrastructure (i.e. buildings), implementing construction planning, and changing land use through planning permissions and permits' granting.

These functions are inherently linked, as the economic, conceptual, and physical uses of land influence its value, which is further shaped by future use possibilities defined by zoning, planning regulations, and permitting processes.

The "*continuum of land rights*" concept, as highlighted by UN-HABITAT (2003; 2008), recognises land rights as a spectrum ranging from informal, customary rights to formally, fully documented legal rights. This framework accommodates the dynamic nature of tenure systems, allowing for the inclusion of those with weaker tenures and promoting equitable land rights recognition and administration (OGC, 2018), as illustrated in Figure 2.2. By adopting this perspective, LAS can be more flexible and better address the complexities of modern LA while fostering inclusivity.

The continuum includes different sets of rights, varying levels of security and responsibility, and different degrees of enforcement. Within the continuum, multiple tenure systems can coexist, and the status of plots or dwellings within a settlement can change, such as when informal settlers are granted titles or leases. Even after being officially replaced by statutory systems, informal and customary tenure systems may continue to be perceived as legitimate, especially when new systems and laws are slow to address increasing or changing needs. In such cases, and where official mechanisms deny the poor legal access to land, people often resort to informal or customary arrangements to access land that would otherwise be unaffordable or unavailable (UN-HABITAT, 2008). For the people to land relations (Figure 2.2), the continuum of land rights should be applicable (Lemmen et al., 2021).

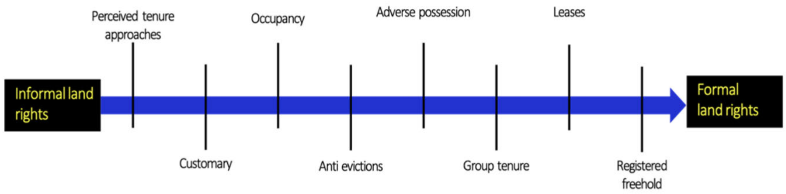

FIG. 2.2 UN Habitat's continuum of land rights (UN Habitat, 2008, adapted)

The scope of ownership rights and their representation in LASs are shaped by legal provisions and Public Law Restrictions (PLRs) (such as zoning regulations, building height restrictions and environmental protection areas). The growing use of vertical spaces and underground infrastructure has led to increasing complexity in PLRs. For over two decades, PLR registration has been a significant research focus

(Zevenbergen et al., 2002; Bennett et al., 2006; Navratil, 2012; CLRKEN, 2015; Kitsakis et al., 2016; 2021), reflecting the need to address these evolving challenges effectively. Countries such as Switzerland and Estonia have developed systematic PLR databases—through cantonal Swiss PLR cadastres and Restriction Information Systems, respectively. Similarly, Denmark, the Netherlands, and Finland have integrated PLRs into their LASs (Kitsakis et al., 2021).

2.1.2 Towards 3D Land Administration

Currently, LASs still predominantly rely on 2D-based systems, relying on planar representations of parcels as the primary unit of property registration (Sun et al., 2022). This reliance on 2D systems presents legal, organisational, and technical challenges (Kalogianni et al., 2020b), as they often fall short in managing the complexities of urban environment.

As the pressure on space in the built-up areas intensifies, particularly in densely used areas, there is a growing need to utilise spaces above and below the earth's surface for sustainable land use. Spatial units now encompass traditional 2D parcels, apartments, underground utilities, marine zones, and 3D air parcels, reflecting a shift towards multi-dimensional space management.

With the increasing importance of land, coupled with pressures from population growth, rapid urbanisation and climate change, methods for land document registration and storage have evolved continuously, advancing alongside technological progress. The integration of various technologies and tools for collecting 3D data, adds complexity and challenges in the ongoing processes of registration, recording, updating, retrieval, and maintenance of RRRs and land-related data. Consequently, there is a pressing need for a 3D LAS capable of efficiently managing these processes to support 3D LA.

The adoption of the LADM and alignment with international standards (see chapter 3) represent a significant step forward. These efforts promote a unified approach for managing land rights and accurately representing 3D land information. A 3D LAS provides a structured method for integrating formal and informal rights, enhancing the inclusivity, robustness, and sustainability of LASs. Such advancements are vital in addressing urbanisation, environmental changes, and societal needs, ensuring land administration remains a cornerstone of equitable governance.

However, the development of 3D LASs has been uneven globally. Some countries and regions have made notable progress, particularly in registering 3D underground objects and developing tailored workflows. For instance, Ramlakhan et al. (2023) propose a comprehensive workflow to model underground RRRs using international standards like LADM and IFC (Figure 2.3). Similarly, Saeidian et al. (2021) introduce a holistic framework addressing the technical, legal, and institutional aspects of 3D underground LA.

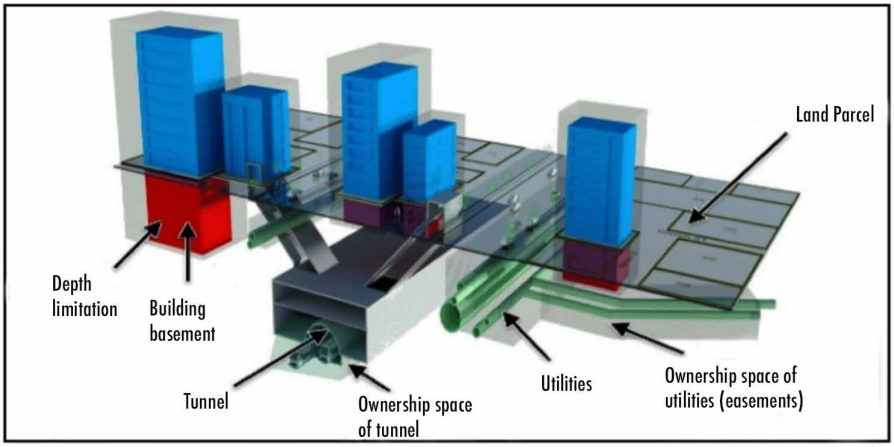

FIG. 2.3 A 3D underground model integrating physical and legal data (Saeidian et al., 2024)

Countries such as Sweden, Norway, Australian states, and Chinese cities like Shenzhen have operational components of 3D LASs (see section 2.3). In contrast, other jurisdictions face organisational, legal, or technical barriers that hinder progress (Lemmen et al., 2003; van Oosterom, 2013, 2018, 2022). Understanding these differences is essential for developing tailored solutions that align with regional needs and constraints. Recognising the diversity of LAS development enables stakeholders to collaborate more effectively on international standards, fostering efficient and equitable LA practices. 3D LASs build upon and support existing 2D LA-related data, ensuring continuity in LASs. Details on countries that have developed 3D LAS based on LADM, are presented in sub-section 4.3.1.

Paasch et al. (2023) provide a comprehensive review of trends in 3D LA, identifying key focus areas from 2012 to 2021. These include legal, organisational, and technical issues, with growing attention to marine applications, valuation, visualisation, BIM, and the emerging concept of 4D cadastre. Further research is needed to determine whether these topics represent enduring trends or temporary interests in the evolving field of 3D land LA.

2.1.3 Legal, organisational and technical aspects of 3D Land Administration

LASs across countries present significant variation due to differences in legal, organisational, cultural, and technical contexts. These variations affect how jurisdictions register, manage, visualise, and disseminate land-related data. In countries such as Australia, the legal and physical dimensions of spatial units are intrinsically linked (Atazadeh et al., 2017). While the legal and organisational perspective primarily focuses on registering land rights and interests, the physical representation of these spatial units becomes essential for broader purposes, such as lifecycle asset management.

Legal interests can exist in 3D even without physical construction. Research has explored the interdependencies between legal objects and their physical counterparts, leading to two primary approaches for defining integrated 3D spatial data models. One method integrates legal information into physical models through built-in extension mechanisms, while the other relies on external links connecting legal and physical models (Kalogianni et al., 2017; Atazadeh, 2017). The former approach ensures the stability and coherence of both dimensions, enhancing the functionality of 3D LASs, while the latter depends heavily on maintaining physical spaces. Integrating these representations enables stakeholders to manage land information effectively, facilitating better decision-making and asset management throughout the lifecycle of spatial units.

The variation in LASs also extends to the degree of technological adoption and innovation. While some countries (like Indonesia (Mulyadi et al., 2022) and Singapore (Wu et al., 2024)) have embraced advanced geospatial technologies, such as BIM, GIS and cadastral databases, to enhance their LA processes, others remain in the early stages of digitising their land records. Idris (2024) organised the existing frameworks that guide the implementation of an electronic LAS into technical and governance-related and based on his systematic review and meta-analysis, he concluded into a comprehensive conceptual framework.

Shahidinejad et al. (2024) conducted a literature review and presented a summary of the most dominant database approaches for 3D LA, outlining the conceptual data models used (e.g., IFC, LADM, CityGML), the methods for data preparation and conversion (e.g., ETL (Extract, Transform, Load) tools, SQL commands, 3DCityDB, scripting), the techniques applied for query analysis (spatial/non-spatial), the evaluation metrics adopted (e.g., query performance, visualisation, hardware and time processing, questionnaires, computational analysis), and the technologies utilised (software, libraries, and tools) in previous research studies.

TOC

The technical aspects of 3D LAS encompass various stages of the digital data lifecycle, which have been extensively studied. These include 3D: data acquisition (Jazayeri et al., 2014), data models and standards (Atazadeh et al., 2018), data validation (Asghari et al., 2019; Karki et al., 2013), data storage (Janecka et al., 2018; FIG, 2018b; Thompson et al., 2021), visualisation (Pouliot et al., 2018; Shojaei, 2014), and data query and analysis (Atazadeh et al., 2019; Barzegar et al., 2021). However, developing an integrated strategy that considers all phases of the 3D cadastral data lifecycle remains a relatively new research area with limited attention (Kalogianni et al., 2020; Olfat et al., 2021).

The formal discussion on 3D Cadastre began in 2002 with the FIG workshop "3D Cadastres", organised by FIG Commissions 3 and 7 and lasted till 2006. This initiative spurred further advancements as cadastral organisations worked to strengthen 3D support within their systems. A milestone came during the 24^{th} FIG Congress in Sydney in 2010, where a dedicated working group, "3D Cadastres," was established to promote research and develop robust frameworks for 3D LASs.

The FIG Working Group identified three key building blocks for 3D LAS: legal, institutional, and technical (Döner, 2021; Lemmen et al., 2003), as described in sub-section 1.1. These pillars represent the legal frameworks, institutional arrangements, and technological infrastructure necessary for effective implementation. Research on these three aspects has been systematically documented in FIG Best Practices (FIG, 2018) and the more recent position papers (van Oosterom et al., 2023).

A substantial effort to evaluate the global status of 3D LAS has been led by FIG Commissions 3 "Spatial Information Management" and 7 "Cadastre and Land Management" through Working Group 7.3 – LADM and 3D LA. Systematic questionnaires[4] have been conducted to assess the current state of 3D LAS implementation and expectations for the near future, with findings detailed in sub-sections 2.3 and 7.1 respectively.

4 https://gdmc.nl/3Dcadastres/participants/

2.2 Global parameters for measuring and advancing Land Administration

Advancing LASs is an ongoing process, essential for aligning with global initiatives, technological trends, and evolving society expectations. Recent research (Kara et al., 2024a; World Bank (2024)) and global development projects underscore the necessity for even traditionally efficient LASs to undergo updates due to the rapid societal changes occurring worldwide (Riekkinen et al., 2016). The need for advancement has become increasingly evident, as international bodies and land professionals, work diligently to enhance LA practices by developing various LASs-related frameworks and models, as detailed in sub-section 2.2.1.

These global initiatives highlight the importance of effective, efficient and integrated LAS that is ongoing upgraded and validated, to ensure data consistency. Achieving data validation and integration in line with global trends is facilitated by employing a robust data model, which serves as a central component in the LAS data lifecycle. LADM can serve this purpose effectively and in this context, research focused on implementing SDGs through LADM is presented in sub-section 2.2.2.

2.2.1 LA-related developments for measuring LAS performance

Achieving LAS reform requires measuring and expressing progress in LA (Lemmen et al., 2017). Various international agencies have developed guidelines, indicators, and tools to support the responsible authorities in measuring and assessing LA advancement (GLTN, 2019). These tools often rely on standardised approaches like LADM/STDM which streamline data collection and provide a comprehensive overview efficiently. However, a universally recognised framework for evaluating LASs globally is still lacking (Chehrehbargh et al., 2024). This gap is largely due to diverse cultural and social contexts (Steudler et al., 2004; Williamson, 1998). Between 1998 and 2022, various initiatives, frameworks, and global indicators were developed, as shown in Figure 2.4, with contributions from organisations such as the United Nations (UN), the World Bank (WB) and the FIG, as well as initiatives like global agendas and performance evaluation studies.

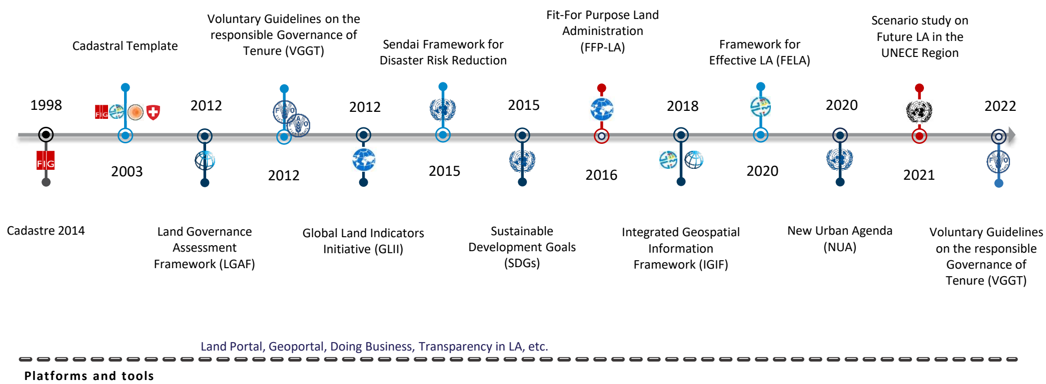

FIG. 2.4 Time series of land-related initiatives (Ehrenberg et al., 2024; adapted)

The United Nations 2030 Agenda for Sustainable Development[5] emphasises the importance of addressing land issue across several targets and indicators. It advocates for reliable data collection, linking statistics and geospatial information while ensuring national ownership and promoting public-private cooperation (Habitat III, 2016; UN, 2018). Adopted by all UN member states in 2015, the 17 Sustainable Development Goals (SDGs) include 169 targets, and 248 indicators, focusing on measurable outcomes for a sustainable future. Land and tenure data are vital for measuring and informing progress, as well as enabling evidence-based policy and decision-making. Figure 2.5 highlights the SDGs related to LA.

Maximising the value of geospatial information, including LA-related data, at both national and sub-national levels is essential for capturing the achievements of the 2030 Agenda. To achieve this within the 2030 Agenda's timeframe, it is essential to adopt and implement relevant standards effectively (Lemmen et al., 2017). In this context, the LADM can play an important role, with its relevance to certain SDGs identified, particularly SDG 1 "No Poverty" (specifically Target 1.4.2, which focuses on secure tenure rights with legally recognised documentation influencing land use), SDG 11 "Sustainable Cities and Communities," SDG 14 "Life Below Water," and SDG 15 "Life on Land" (Kara et al., 2023c), as presented in sub-sections 2.2.2 and 4.2.

5 https://sdgs.un.org/2030agenda

FIG. 2.5 Land Administration and SDG's (de Zeeuw, 2016)

The United Nations Economic and Social Council (ECOSOC) established the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM)[6], as the apex intergovernmental body for geospatial information management. It provides direction on the production, availability, and use of geospatial data within national, regional, and global policy frameworks, addressing global challenges and supporting development agendas (UN-GGIM, 2019b). Recognising the need for harmonised geospatial data to support sustainable development, UN-GGIM introduced the Fundamental Geospatial Data Themes. These 14 themes (Figure 2.6), ranging from Geographic Names and Addresses to Land Cover and Land Parcels, aim to bridge the gap between geospatial data and other stakeholders, facilitating the achievement of the Sustainable Development Goals (UN-GGIM, 2019a).

The Integrated Geospatial Information Framework (IGIF), adopted by the UN-GGIM in 2018, guides nations in developing and strengthening geospatial information systems to support sustainable development. Structured around governance, technology, and people, the IGIF promotes data collection, management, and dissemination to enable evidence-based decisions.

6 https://www.un.org/geospatialnetwork/

TOC

FIG. 2.6 UNGGIM Fundamental Geospatial Data Themes (UNGGIM, 2019a)

Similarly, the Framework for Effective Land Administration (FELA) is a high level, strategic reference for UN member states in the process of building, enhancing, monitoring, and evaluating their LASs (de Zeeuw et al., 2020; UNGGIM, 2019c) and aligns with IGIF (UNGGIM, 2019c). FELA offers nine pathways to improve LAS and meet SDG targets through governance, policy, innovation, and standards and make direct reference to the underlying pragmatic philosophy, elements, and guidance of FFPLA.

Global initiatives such as the Global Land Indicator Initiative (GLII) and the Land Governance Assessment Framework (LGAF) further support land governance by providing tools to monitor land tenure, valuation, and use. GLII, established under the Global Land Tool Network, aims to support efforts to harmonise monitoring efforts around land tenure and governance (GLTN/UN Habitat/Kadaster, 2015). Whilst LGAF highlights areas where a country is doing well and where there are deficiencies building consensus for land sector reform. LGAF also provides tools to monitor land governance as reform (World Bank, 2013; World Bank, 2019). Currently, there are no indicators directly related to 3D, however the GLII and LGAF, use 3D information as input for the collection and management to develop land indicators.

The Fit-for-Purpose Land Administration (FFPLA) approach complements these frameworks by providing scalable solutions for tenure security, prioritising complete coverage over technological advancements. Together, these initiatives address global challenges while aligning with sustainable development goals, ensuring LAS remain relevant, reliable, and adaptive in the face of future demands (Enemark et al., 2015a; Kelm et al., 2021). The fit-for-purpose concept is succinctly described by Enemark et al. (2015b) as "*as little as possible – as much as necessary.*" The FFPLA approach is considered a top-down, participatory method for recording parcel information, prioritising complete coverage first (de Zeeuw et al., 2020). Bennett et al. (2021b) provide a review of LA from the perspective of LAS maintenance in alignment with FFPLA developments, proposing a model for analysing maintenance in LA and identifying solutions to maintenance challenges based on FELA's strategic pathways.

At European level, the INSPIRE Directive mandates EU Member States (MS) to monitor and report on the implementation and use of their Spatial Data Infrastructures (SDIs)[7]. This process is guided by specific indicators designed to assess compliance and progress in SDI development. According to the Commission Implementing Decision (EU) 2019/1372[8], MS calculate monitoring indicators using metadata from spatial datasets and services published through their discovery services. These indicators measure the implementation progress of the Directive and evaluate its overall success.

The evaluation of INSPIRE implementation relies on key indicators. The availability of spatial data and services assesses the extent to which datasets and services are accessible to users. Metadata conformity measures the degree to which metadata complies with INSPIRE standards, while the conformity of spatial datasets evaluates adherence to the required specifications. The implementation and performance of network services that facilitate the discovery, viewing, and downloading of spatial data are also monitored. Additionally, data-sharing effectiveness is assessed by examining the collaboration between public authorities and other stakeholders. These indicators create a structured framework for evaluating INSPIRE implementation across MS, ensuring that spatial data infrastructures are consistently developed and maintained to support interoperability and harmonisation at a European level.

Finally, global challenges like climate change, natural disasters, urbanisation, wars/conflicts and resource insecurity create new demands for LAS to adapt to evolving user needs and community expectations (UNECE, 2021). LASs play a critical role in addressing intersectoral priorities, such as e-government, smart cities, spatial data infrastructure, and climate change initiatives, while addressing financial, technological, legal, and organisational constraints. Key considerations include how LA authorities can ensure relevance, reliability, and trustworthiness in their systems. The UNECE (2021) study highlights megatrends and drivers in LA (such as demographic change, digital transformation and urbanisation), offering scenarios to guide decision-makers (see Figure 2.7). Strategic planning should align with global principles, such as the UN-GGIM Framework for Effective Land Administration, to ensure effective responses to these challenges.

7 https://knowledge-base.inspire.ec.europa.eu/monitoring-and-reporting_en#:~:text=According%20to%20the%20Commission%20Implementing,to%20report%20to%20the%20Commission
8 https://eur-lex.europa.eu/eli/dec_impl/2019/1372/oj/eng

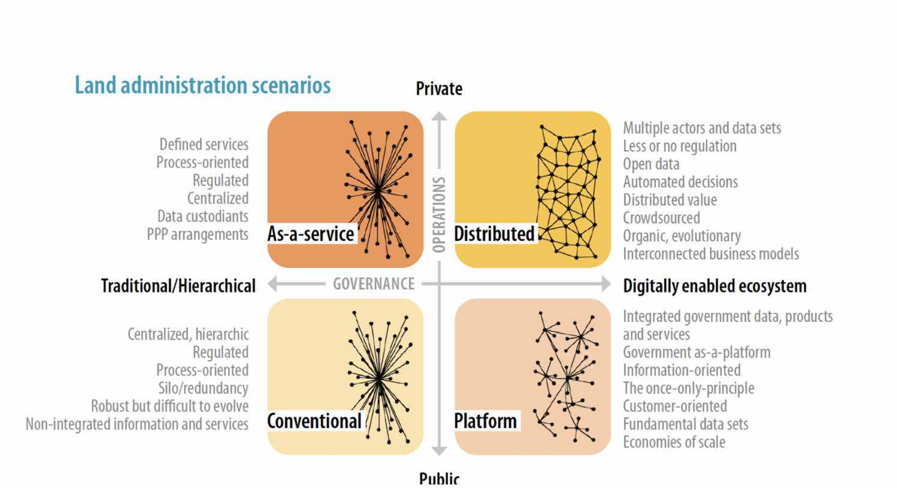

FIG. 2.7 LA scenarios and their characteristics (UNECE, 2021)

2.2.2 Computing and reporting land-related indicators

Despite challenges in securing timely data across all SDGs, considerable progress has been achieved in the availability of internationally comparable data. The number of indicators in the global SDG database increased from ~115 in 2016 to 225 in 2023, with data records growing from 330.000 in 2016 to 2,7 million by May 2023 (UN, 2023). Additionally, substantial advancements have been achieved in the methodological development of SDG indicators. By March 2020, all indicators had well-established internationally agreed methodologies, ensuring comparability, accuracy, reliability, and usefulness. The proportion of indicators that are conceptually clear and have good country coverage has also risen significantly from 36% in 2016 to 66% in 2022 (UN, 2023).

I Computing land related indicators

Unger et al. (2019; 2021) proposed an alignment between SDGs and the core classes of the LADM and the STDM (Figure 2.8). Their work highlights the potential of leveraging these domain models to support the achievement of SDG targets, particularly those related to land tenure, property rights, and sustainable land use. However, the proposal lacks specific details or methodologies for implementing this alignment.

TOC

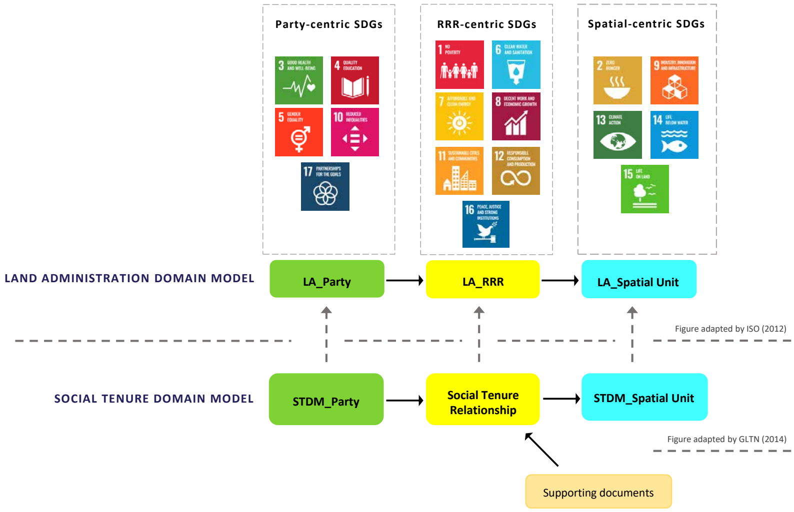

FIG. 2.8 LADM as basis for the SDGs (Unger et al., 2021; adapted)

Unger et al. (2021) examined selected SDG indicators related to gender and land, highlighting their implications for LADM and identifying specific queries to monitor and report progress toward these indicators. The importance of metadata for SDG indicators was also noted, as it provides critical information for accurate measurement, monitoring, and reporting of progress (Fraisl et al., 2020). Addressing the lack of standardisation in SDG indicator metadata, Chen et al. (2024) proposed a ‘four-step’ method to formalise SDG land-related indicators. This method was validated using four selected indicators, one of which is depicted in Figure 2.9.

Chen et al. (2024) added methods and procedures to existing LADM classes to enable indicator calculations. They also developed blueprints for external classes to address additional information needs and interface classes to display indicator values specific to countries and reporting years. These advancements support compatibility with other ISO standards and provide a structured approach to calculating indicators. This would help eliminate ambiguities, improve computational efficiency, and ensure more accurate indicator values that better reflect SDG realisation.

An example of this approach is presented in Figure 2.9, where the UML (Unified Modelling Language) model for the calculation of SDG 1.4.2. is illustrated.

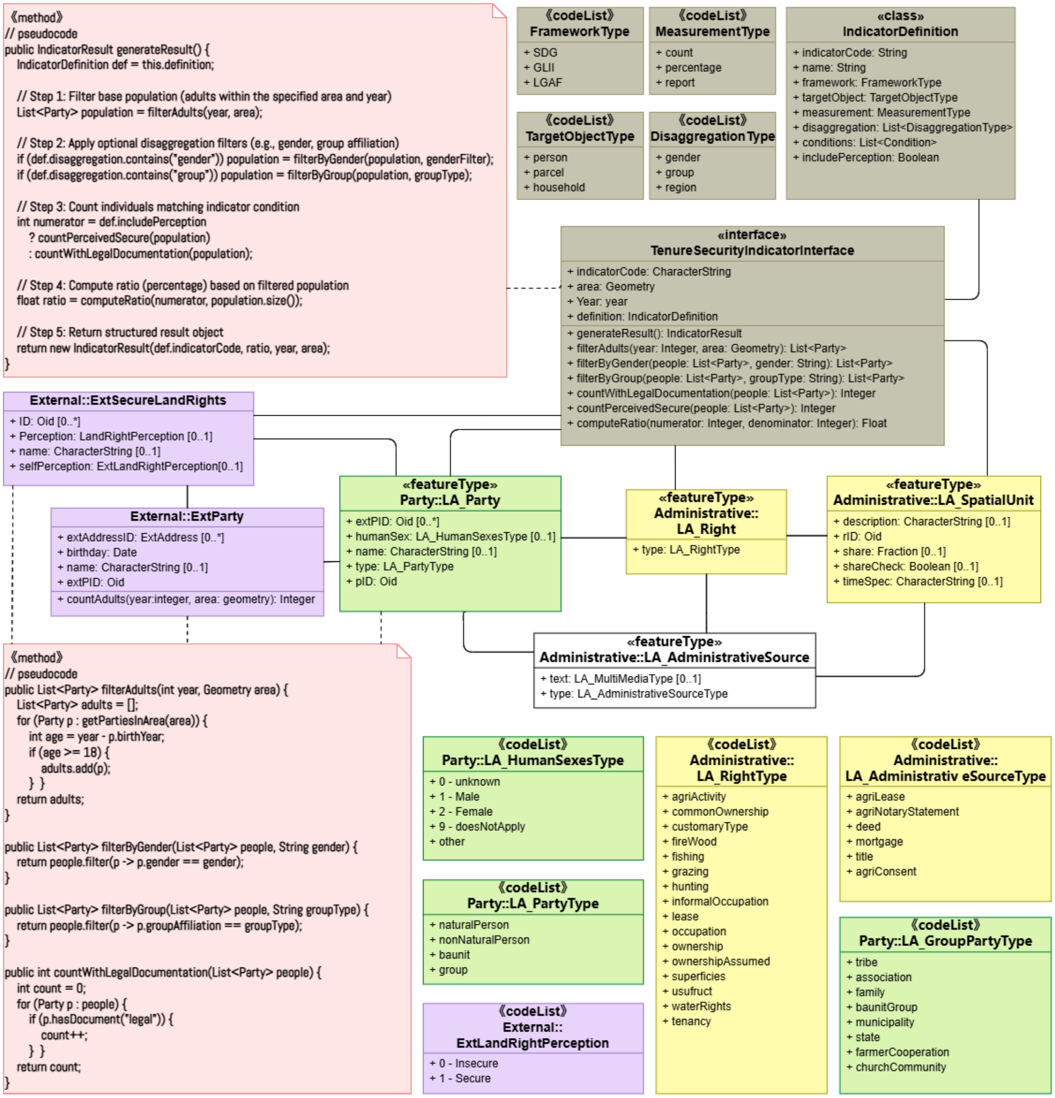

FIG. 2.9 Modelling SDG Indicator 1.4.2 calculation based on LADM (Chen et al., 2024)

Based on the conceptual model (Figure 2.9), Chen (2024) developed a database to calculate and manage SDG Indicator 1.4.2, which measures tenure security. The database incorporates the creation of custom data types to ensure data consistency, while functions and triggers are implemented to enforce data integrity and automate processes. Additionally, the system facilitates the generation of reports for monitoring and analysis, providing a robust and scalable solution for managing land tenure data and reporting progress towards SDG 1.4.2.

Following, Kara et al. (2024b) build upon the work of Chen et al. (2024) and conduct a study concluding that LADM is capable of monitoring a significant proportion of LGAF and GLII indicators. However, it is noted that many indicators are heavily influenced by a country's national legislation, its implementation practices, organisational structures, and institutional capacity. This highlights the need for a flexible approach that incorporates both technical and governance considerations when aligning international standards like LADM with global land governance and monitoring frameworks.

II Reporting land-related indicators

Several countries have established procedures for collecting land-related information, but these processes are often outdated, expensive, and time-consuming, relying on resources that may be unavailable. The technologies required for data collection and management are complex and sometimes inaccessible, or not compliant with national or international standards, particularly for registering undocumented people-to-land relationships. However, the unprecedented demand for data, driven by the 2030 Agenda, has spurred innovation in data collection, incorporating non-traditional sources such as administrative records, satellite imagery, and citizen-generated data to bridge data gaps (UN, 2023). The integration of multiple data sources has become increasingly common, with National Statistical Offices prioritising capacity building in these areas, as depicted in Figure 2.10.

Continued efforts to standardise methodologies and address gender disparities are essential for improving the quality and coverage of land-related indicators worldwide. Platforms like Prindex[9], the Global Property Rights Index remain critical in filling these gaps and informing global policies to strengthen land governance and tenure security. Prindex measures perceptions of land and property tenure security worldwide by calculating indicators for SDGs through data collection and analysis on people's perspectives of tenure security. This is essential for monitoring several

9 https://www.prindex.net

TOC

SDGs, particularly indicator 1.4.2, which tracks the proportion of the population with secure tenure rights. Through systematic surveys and robust data analysis, Prindex provides valuable insights that contribute to understanding and monitoring of multiple SDGs, helping to assess and promote tenure security globally.

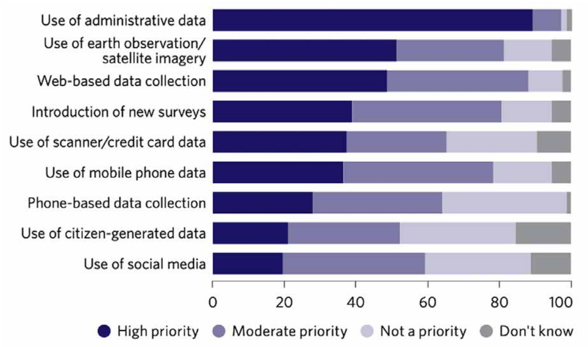

FIG. 2.10 Capacity building priorities identified by national statistical offices, as of July 2021 (UN, 2023)

The status of countries reporting land-related indicators in such platforms highlights a growing recognition of the importance of land tenure security for sustainable development. While many countries actively report data, challenges persist in achieving global consistency, particularly in low-resource settings. Many countries lack the resources to collect and report land-related information systematically, while in regions with high levels of rights' informality, accurate measurement remains challenging. Reporting on women's land rights is improving but remains inconsistent.

2.3 3D LAS around the world: a snapshot at the end of 2022

The FIG Working Group “3D Land Administration and Land Administration Domain Model” conducts a questionnaire every four years, starting in 2010, to report and assess the status and progress of 3D LAS. The initial “*Questionnaire on 3D Cadastres*” in 2010 documented the state of 3D LA in participating countries and their expectations (at that time) for 2014. The questionnaire, initiated in its first edition, aims to address the most important aspects related to 3D LAS and it occurs every four years to capture technological developments and legal advances within each country.

During the FIG Working Week 2023 in Orlando, it was decided to rename the FIG Working Group to “*3D Land Administration and Land Administration Domain Model*” (3D LA & LADM) to reflect the close relevance and the advancements in the field, officially including LADM within its scope. For consistency reason, the questionnaire has been renamed into “*Questionnaire on 3D Land Administration”*, with its most recent version, the “*4th Questionnaire on 3D Land Administration”*, building upon the previous ones on 3D Cadastres.

The responses to all four questionnaires (available via the participants’ page of the 3D LA & LADM Group website)[10] were analysed and reported in various publications (van Oosterom et al. 2011; van Oosterom et al. 2014 and Shnaidman et al., 2019). This analysis revealed that, despite considerable research and advancements, no country had successfully implemented a fully operational 3D LAS. The functionality of existing systems was often constrained, with some only capable of registering volumetric parcels in public registers without integration into a comprehensive 3D digital cadastral map or limited to specific objects using ad hoc semi-3D solutions, such as buildings or infrastructure (van Oosterom et al., 2011). Shnaidman et al. (2019) identified that the primary barriers to achieving fully functional 3D Land Administration Systems (LAS) stem from either legislative issues—such as the definition of parcel in legislation which is often land related (2D) and not 3D space related—or technological and organizational challenges.

For the 4th questionnaire, all members-countries of the Working Group were invited to report on the status of their 3D LAS as of the end of 2022 and outline their expectations for 2026.

10 https://www.gdmc.nl/3DCadastres/participants/

Countries active in the 3D LA domain, but not previously involved in the questionnaire were also encouraged to participate. The purpose of this initiative is to create a comprehensive inventory of global practices, enabling countries to share experiences, foster collaboration, and support the advancement of 3D LA initiatives.

The questionnaire's structure, originally established in its first edition, has been preserved to allow for analysis and comparison of developments over time. Nevertheless, specific questions have been refined to improve clarity for respondents and to better reflect the evolving roles and functional requirements of LASs. These refinements also address emerging topics in 3D LA., ensuring the questionnaire remains up-to-date with advancements in the domain.

New additions reflect key developments, such as the integration of BIM in LA, the development of innovative 3D LA applications, and the implementation of the LADM. By incorporating these advancements, the questionnaire remains a relevant and effective tool for capturing the evolving landscape of 3D LA and ensuring comprehensive data collection for future research and policy development.

The questionnaire is structured into 13 comprehensive sections, each addressing distinct aspects of 3D LAS to capture a detailed overview of their status and development expectations, specifically:

1. Section 1 focuses on the description of general and applicable real-world 3D situations.
2. Section 2 report on the registration of infrastructure and utility networks, highlighting the management of subsurface and above-ground assets.
3. Section 3 addresses the relationship between 3D properties and constructions, particularly apartments and condominiums.
4. Section 4 delves into the use of X/Y coordinates for spatial referencing.
5. Section 5 explores the representation and registration of the third dimension, specifically height and depth.
6. Section 6 considers the inclusion of temporal issues (the fourth dimension) in LAS, focusing on time-based changes and updates.
7. Section 7 analyses the registration of Rights, Restrictions, and Responsibilities (RRRs) within a 3D context.
8. Section 8 reviews the structure and functionalities of the Digital Cadastral Database (DCDB).
9. Section 9 evaluates cadastral survey plans, including their content, processes, and associated field sketches.
10. Section 10 investigates the dissemination of 3D LA-related information.

11 Section 11 collects statistical information on the country's LAS, providing a quantitative perspective.
12 Section 12 offers reflections and remarks from questionnaire participants, enabling qualitative insights.
13 Section 13 concludes with the contact details of participants, facilitating future collaboration and follow-up.

This thorough structure ensures that the questionnaire provides a holistic understanding of 3D LAS across multiple dimensions, while enabling analysis of developments and identifying areas for future improvement.

Table 2.1 provides the participation of countries in the recurring questionnaire from 2010 to 2022. Participation across continents underscores the global significance of this initiative, with representation from regions like Europe, Asia, Africa and America. The data indicates steady participation from countries like Argentina, Australia (several states), Canada (Quebec), China (Shenzhen), Greece, Finland, and Turkey, showcasing their ongoing commitment to advancing LAS and contributing to global knowledge sharing. The regular participation provides a reliable benchmark for assessing global LAS trends and helps identify emerging best practices. These countries often report progress in adopting advanced technologies, implementing standards such as the LADM, and addressing complex urban and rural land management challenges.

However, while the table reflects the steady involvement of certain nations, it also reveals inconsistencies in reporting from others, such as Germany, Austria, and Bahrain, whose participation has been intermittent. These irregularities could stem from various factors, including shifting national priorities, political changes, resource constraints, or organisational issues, such as insufficient engagement by the designated representatives tasked with completing the questionnaire.

Furthermore, the inclusion of sub-national regions, such as Shenzhen in China and Delta State in Nigeria, underscores the significance of decentralised approaches in specific jurisdictions. This suggests that some areas may prioritise localized governance or policy-making frameworks that align with their unique contexts. Notably, the participation of new entrants, such as Western Australia in the latest questionnaire round, is an encouraging sign of expanding engagement.

TABLE 2.1 Overview of the countries that participated in the questionnaires on 3D LA from 2010 till 2022 (Kalogianni et al., 2023b; adapted)

Countries that participated	Year of questionnaire completion			
	2010	2014	2018	2022
Argentina	√	√	√	√
AUS, Queensland	√	√	√	√
AUS, Victoria	√	√	√	√
AUS, New South Wales			√	√
AUS, Western Australia				√
Austria	√			√
Bahrain	√			√
Brazil	√	√		√
Canada, Quebec	√	√	√	√
China, Shenzhen provincial city	√	√	√	√
Costa Rica		√	√	
Croatia	√	√	√	√
Cyprus	√	√	√	√
Czech Republic		√	√	√
Denmark	√	√		√
Finland	√	√	√	√
France	√			
Germany	√	√	√	
Greece	√	√	√	√
Hungary	√	√	√	
Iceland				√
India (Delhi State)	√	√	√	
Indonesia	√		√	√
Israel	√	√	√	√
Italy	√			
Kazakhstan	√			
Kenya	√	√	√	√
Malaysia	√	√	√	√
Montenegro				√
Nepal	√			√
The Netherlands	√	√	√	√
New Zealand			√	√
North Macedonia	√	√		
Nigeria (Delta State)	√	√	√	
Norway	√	√		
Poland	√	√	√	√
Portugal		√	√	√

>>>

TOC

TABLE 2.1 Overview of the countries that participated in the questionnaires on 3D LA from 2010 till 2022 (Kalogianni et al., 2023b; adapted)

Countries that participated	Year of questionnaire completion			
	2010	2014	2018	2022
Russian Federation	√			
Scotland			√	√
Serbia		√	√	√
Singapore		√	√	√
Slovenia			√	√
South Korea	√	√	√	√
Spain	√	√	√	√
Sweden	√	√	√	√
Switzerland	√	√	√	√
Trinidad and Tobago	√	√	√	√
Turkey	√	√	√	√
England and Wales, United Kingdom	√			

Figure 2.11 illustrates the distribution of participating countries across continents, demonstrating broad geographic coverage and a well-balanced representation of most regions. This distribution ensures that insights from diverse legal, organisational, and technical contexts are captured, contributing to a comprehensive global perspective on 3D LA developments.

FIG. 2.11 Spatial distribution per continent of the countries that have participated in the 4th Questionnaire of 3D Land Administration (status of 2022 and expectations for 2026) (Kalogianni et al., 2023b)

To ensure consistent interpretation and comparability of results across countries and over time, the questionnaire follows a structured approach based on clearly defined concepts. Specifically, the concept of 3D LA, including 3D parcels (or 3D spatial units as per LADM), is understood in the broadest sense. However, its precise definition varies depending on the legal and organisational framework of each country, state, or province. In this context, 3D parcels include both land and water spaces, extending above and below the earth's surface.

Moreover, a 3D parcel or spatial unit is regarded as a legal object representing a part of space, often linked to a physical object in the real world that can also be described in 3D. Distinguishing between these two types of objects is essential, as 3D LA focuses on the spatial and legal dimensions rather than the physical attributes of these objects.

The conceptual model and terminology of the questionnaire align with ISO 19152:2012 (ISO, 2012), while also incorporating elements from the upcoming LADM Edition II, which expands the standard into six parts. This approach ensures a standardised and comprehensive framework for analysing and interpreting 3D spatial units across different jurisdictions.

Although LADM is an ISO standard with well-defined concepts, and the questionnaire provides explanations and examples from previous editions, ambiguity in responses persists. Participants interpret certain concepts differently based on their legal, organisational, and technical contexts, leading to inconsistencies in how data is reported. Additionally, variations in statistical data collection methods impact comparability across countries.

Table 2.2 highlights disparities in the number of 2D and 3D parcels reported by countries, contextualised by geographic size and population data. The responses reveal differing perceptions and definitions of 3D parcels. In some countries, such as Trinidad and Tobago, condominiums and apartments—often considered 3D parcels—are not explicitly registered as such. In many cases, including Bahrain, 3D parcels are not distinguished separately but integrated within 2D parcel records, while, in the Netherlands only two parcels appear to be registered as 3D. Furthermore, in some jurisdictions, 3D parcels are not always surveyed but instead recorded using a 3D index map, reflecting variations in cadastral practices and spatial accuracy requirements. A similar issue applies, to a limited extent, for 2D parcels, where reported figures may be estimates rather than comprehensive surveys, as seen in Trinidad and Tobago. Additionally, Croatia and the Netherlands include water territories in their reported land area, offering a broader perspective on LA scope.

TABLE 2.2 Statistics about the number of parcels from the participating countries (Kalogianni et al., 2023b)

di#	Countries reported the statistics of parcels	Size of county/ jurisdiction in sq km	Number of 2D parcels	Number of 3D parcels	Population (last data available)
1	Argentina	2.780.000	About 20 millions	0	47,4 millions
2	AUS - NSW	809.444	4.5 million	100.000+	8,1 millions
3	AUS – Queensland	1.730.648	2.252.878	3.069 (volu-metric) & 274.095 (build-ing format)	5.296.098
4	AUS – Western Australia	2.642.753	1.1 million	479	2,8 millions
5	Bahrain	786,5	255.436 (including the 2D parcels with 3D aspects)		1.463 million
6	Brazil	8.510.345,538	-	-	207 million
7	Canada-Quebec	~ 1,7 millions	~3.900.000	~ 620.S000	8,7 millions
8	Croatia	56.594 land & 31.067 water	14.5 million	-	3,87 millions
9	Cyprus	9.252	~ 1.600.000	~162.000	~. 865.000
10	Czech Republic	78.866	22.712.065	0	10,52 millions
11	Finland (Case Espoo: & Case Tampere & Case Kajaani & Case Kuopio & Case Lempäälä)	6.182	738.000	171.390	16
12	Greece	131.944	~12.000.000	0	10,43 millions
13	Iceland	137.264	79.087	0	386.639
14	Montenegro	13.812	-	-	619.211
15	Nepal	-	31.895.591		29.136.808
16	New Zealand	268.021	2+ million	145.000+	~5 millions
17	Poland	312.680	38.102.232	0	37.827.000
18	Serbia	88.499	18.948.505	0	6.844.000
19	Singapore	721.5	1.7+ million	-	5,61 millions
20	South Korea	-	45 million	-	55 millions
21	Spain	505.990	53.097.474	~20.000.000	47.420.000
22	Sweden (Stockholm City & Gothenburg City & Malmö City)	808	165.130	492	1.918.068
23	Switzerland	41.285	4.000.000	~1.400.000	8.740.000
24	The Netherlands	33.883 land & 7.643 water	~ 9.000.000	~2	~ 17.500.000
25	Trinidad and Tobago	~ 5.000	~ 500,000 (it is an estimation, they are not surveyed)	0	~ 1.5 million
26	Turkey	784.000	58.7 million	-	84.7 millions

These variations in data reporting highlight the growing importance of 3D parcels, which frequently represent building structures or condominiums. They also underscore the diverse priorities, methodologies, and challenges faced by different countries in managing parcel registration and adapting to evolving LAS requirements.

As previously noted, one of the main barriers to establishing an effective 3D LAS lies in the legislative framework, particularly the definition of a 3D parcel. Responses to Question 1.9 of the questionnaire, '*Is there legislation (law and/or regulations) for 3D descriptions of parcels?*', are shown in Figure 2.12. The majority of participants reported that legal provisions exist for 3D parcel descriptions, while 14% indicated that although the third dimension is not explicitly defined, related legal documents provide partial or indirect references. Nearly one-quarter of the countries stated that no legislation currently exists for defining 3D parcels.

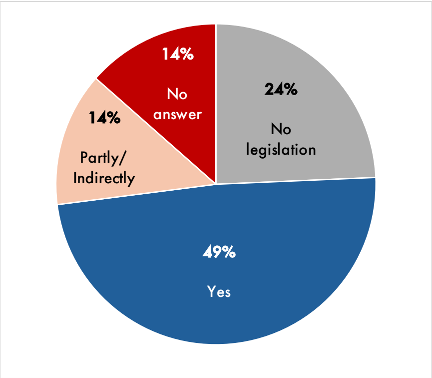

FIG. 2.12 Responses from the participant countries regarding the existence of legislation for the description of 3D parcels (Kalogianni et al., 2023b; adapted)

The introduction of new questions in that questionnaire provided valuable insights into the knowledge, awareness, familiarity, and adoption of the LADM among respondents. The findings revealed that as of the end of 2022, only four of the thirty-seven participating countries—Shenzhen (a provincial city in China), Finland, Malaysia, and Scotland—reported implementing LADM as a formal model for 3D parcels. Singapore indicated that LADM adoption was under investigation, while Sweden reported using LADM conceptually.

While LADM implementation is not obligatory and its scope explicitly states no interference with national legislation, 35% of respondents reported that their cadastral database is based on LADM. These responses reflect varying levels of compliance, ranging from databases that are partially or fully aligned with LADM to those not explicitly mapped to its concepts, as well as systems relying on specific software tools for compliance, which claim to be LADM-compliant (such as Trinidad and Tobago's use of Trimble Landfolio). These variations highlight the diverse approaches and levels of progress in adopting LADM, underscoring the need for further efforts to harmonise its implementation globally.

As illustrated in the right part of Figure 2.13, nearly half of the participating countries (49%) have not -yet- developed an LADM-based country profile. Of those that have developed a country profile (46%), 41% reported that the profile is either at a preliminary stage (e.g., involving only a mapping between LADM classes and corresponding LAS concepts) or has been developed by academic institutions and is accessible through relevant publications (left part of the figure).

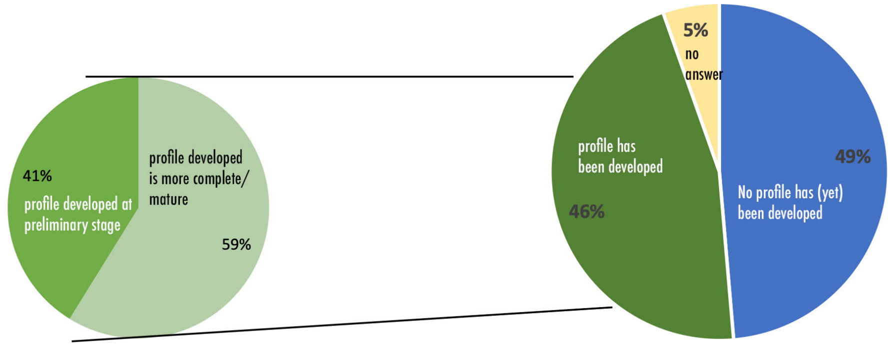

FIG. 2.13 Responses from participants regarding the development of ISO19152:2012 LADM- based country profile (Kalogianni et al., 2023b)

Thompson et al. (2023) developed an initial assessment rubric based on the analysis of questionnaire responses to evaluate the progress of countries in implementing 3D LASs over the past 16 years. This rubric provides a structured scoring framework across nine sections of the questionnaire, as detailed in Table APP.1.1 of ANNEX. Designed as a preliminary tool for quantifying responses and tracking advancements in 3D LAS implementation, it forms part of the ongoing work of the FIG Working Group on 3D Land Administration. While offering a systematic evaluation approach, it is a first-time development with acknowledged limitations, as outlined in ANNEX.

Using this rubric, rankings were calculated for eight countries—Greece, The Netherlands, South Korea, Turkey, China, Spain, Argentina, and Queensland—enabling comparisons with previous questionnaire editions. The results are visualised through diagrams to highlight trends and pinpoint areas for improvement in global LAS development. The findings for Greece, The Netherlands, and Queensland are presented below, while visualisations for Turkey, China, Spain, Argentina, and South Korea are included in the ANNEX, offering further insights into the progress and trends in 3D LAS implementation across these jurisdictions.

Figure 2.14 illustrates the evolution of Queensland's 3D LAS implementation across multiple assessment categories from 2010 to 2022. The figure highlights consistently strong performance in Section 6b (Title Legality), demonstrating well-established legal framework. However, Sections 4 (Coordinates) and 5 (Height) show persistently lower scores, indicating ongoing challenges in height management. Over time, improvements can be observed in newer categories such as Sections 9a (Survey) and 9b (Connection), reflecting advancements in survey integration and data connectivity. The graphical representation provides a comparative overview of progress and areas requiring further development, guiding future enhancements in Queensland's 3D LAS framework.

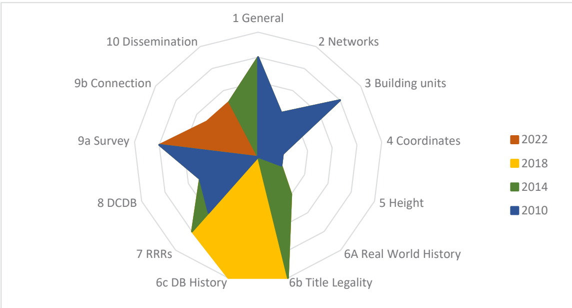

FIG. 2.14 Queensland's scoring in the various sections of the questionnaires, over the years (Thompson et al., 2023)

For the Netherlands, as depicted in Figure 2.15, a significant drop in Section 6b–Title Legality, is observed in the last two editions, with a score of '0', reflecting the absence of titles in the country's cadastral system. However, clear progress in Section 7 (RRRs) demonstrates advancements in managing Rights, Restrictions, and Responsibilities, with scores increasing to '8' in the most recent questionnaire.

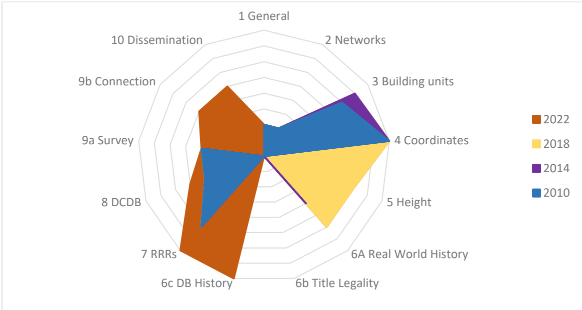

FIG. 2.15 The Netherlands' scoring in the various sections of the questionnaires, over the years (Thompson et al., 2023)

Greece, as depicted in Figure 2.16, highlights differences in its LAS performance across the years. While some sections, like general capabilities (Section 1), demonstrate steady scores, others, such as Section 6b (Title Legality) and Section 8 (DCDB), show variation over the years. This suggests an uneven pace of LAS development in addressing different aspects of 3D LA, which can be justified since the advancements of 3D LA in Greece are not (yet) implemented, but they are researched in theoretical level.

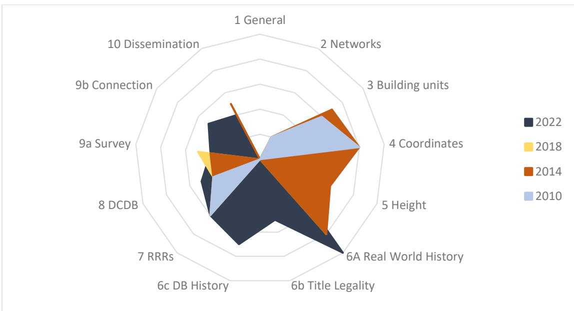

FIG. 2.16 Greece's scoring in the various sections of the questionnaires, over the years

The diagrams highlight the diversity in 3D LAS implementation strategies across surveyed jurisdictions, showcasing both strengths and areas needing improvement. For instance, Queensland demonstrates strong legal frameworks, whereas Greece requires further development in spatial data management. The addition of new sections, such as 9b, reflects evolving priorities in 3D LAS, particularly the connection between survey plans and the DCDB, offering new dimensions for assessing progress. These visualisations are helpful in identifying global trends and formulating targeted recommendations to enhance LAS.

Each country was evaluated across all questionnaire sections using the established ranking scale, with the Manhattan distance (i.e. the average of all scores in a given year) calculated to track changes over time. Furthermore, the average scores for 2010, 2014, 2018, and 2022 were computed and visualised in Figure 2.17, providing a clear representation of the progression in 3D LAS implementation. This analytical approach offers a comprehensive overview of how 3D LAS has evolved across the surveyed countries, highlighting advancements and pinpointing areas requiring further attention.

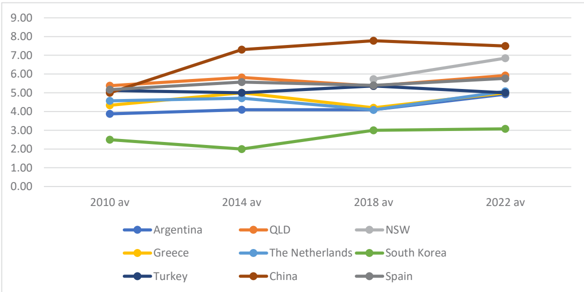

FIG. 2.17 Total score computed for 8 countries using the rubric assessment for their responses at the four questionnaires, 2010-2022 (Thompson et al., 2023)

2.4 Summary

Answering part of the **Sub-RQ1a "What is the current state-of-the-art in 2D and 3D Land Administration around the world, as documented by global reports and reported by countries"**, this chapter provides a comprehensive analysis of the global evolution and current status of LA, with an emphasis on the transition towards 3D LASs. It provides historical context, showcasing LA as a cornerstone of societal governance that has evolved to address increasingly complex legal, organisational, and technical demands. As the urban environment grow multi-dimensional, the need for comprehensive 3D LASs has heightened, necessitating advancements in technology, legal frameworks, and institutional arrangements to effectively manage RRRs. The insights presented in this chapter set the stage for understanding the current landscape of 3D LA and its future trajectory, to be further elaborated in chapter 7, underscoring the critical role of standardisation and advanced technologies in meeting the growing demand for efficient space utilisation in urban areas.

TOC

The integration of LASs within broader global frameworks, particularly in the context of sustainable development, is also examined. Land is a crucial element in global development discourse, and LASs provide essential data for monitoring progress towards international targets, such as the SDGs. With development agencies, like the World Bank, increasingly supporting LA reforms to formalise property rights and enhance services, there is a growing need for reliable mechanisms to measure and assess LAS performance. The chapter highlights methodologies and indicators developed for this purpose, emphasising the importance of adopting international standards, particularly the LADM, to ensure consistent, comparable, and scalable data collection across jurisdictions.

The analysis of the 4th FIG Questionnaire on 3D Land Administration further enriches this discussion, providing insights into the implementation status and expectations for 3D LASs across 37 countries for the term 2022–2026. The findings reveal that, while significant research and advancements have been achieved, further work is required before country can realise a fully operational 3D LAS. The chapter underscores the need for sustained collaboration and knowledge sharing to overcome these obstacles and facilitate the global transition towards integrated 3D LASs.

To initiate the standardisation of the evaluation of 3D LAS implementation, this chapter introduces an assessment rubric developed to rank countries based on their questionnaire responses. This tool enables systematic comparison across jurisdictions and provides a foundation for future refinements. Importantly, the rubric demonstrates the advantages of implementation guided by standards, such as LADM, rather than relying solely on reports and metadata. Standards offer flexibility, enabling frequent, region-specific reporting with more detailed results and changes, and organise existing information into actionable insights. These structured methodologies could also be incorporated into Part 6 of LADM Edition II to support the formalisation of SDG indicators.

The integration of legal, organisational, and technical components remains critical for advancing 3D LASs. Aligning these elements with international standards, like LADM, ensures consistency, interoperability, and adaptability to evolving urbanisation and land use challenges. By fostering innovations in these domains and embracing standardised frameworks, stakeholders can achieve resilient, inclusive, and sustainable LASs. These systems are essential for equitable governance and the effective management of land resources in a rapidly changing global context.

3 State of the Art in Standardisation of (Geo) Information Management for the Built Environment

[Sub-RQ2] **Which standards can support data reuse in the context of SDL, particularly in the context of 3D Land Administration?**

This chapter is based on the following publications:
Kalogianni, E., *Dimopoulou, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2020). BIM/IFC files for 3D real property registration: an initial analysis. In Proceedings: FIG Working Week 2020, pp. 1-22, part of ISBN: 978-87-92853-93-6/*
Kalogianni, E., *Dimopoulou, E., Gruler, H.C., Stubkjær, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2021). Developing the refined survey model for the LADM revision supporting interoperability with LandInfra. In Proceedings: FIG Working Week 2021, pp. 27, part of ISBN: 978-87-92853-65-3*

ABSTRACT

Integrating Architecture, Engineering, Construction, Owner Operator (AECOO), geospatial, and economic data into a seamless flow across the Spatial Development Lifecycle—from planning to operations—is challenging, largely due to the need for consistent data reuse as well as high-quality data. Efficient data reuse adds value by minimising errors and incorporating real-world coordinates, benefiting all stakeholders. This sets the stage for a deeper exploration of how standardised practices facilitate interoperability and efficacy of geo-information systems across various sectors. Interoperability, data sharing, and integration are essential for managing of 3D spatial units, particularly in LA. There is broad consensus that vendor-neutral,

standardised data models and formats are crucial to support data reuse and meet the diverse needs of the involved disciplines. These models ensure uniform data exchange across different systems, as discussed in section 3.1, while highlighting the significance and power of partnerships in developing professional standards for land and the built environment.
Standardisation plays a key-role in achieving data interoperability, reuse, and consistency throughout the lifecycle. International standards like BIM/ IFC, and LandInfra have evolved to harmonise data formats and improve data flows between systems, particularly in urban planning, design, construction, and LA. These concepts are explored in sections 3.2 and 3.3. Additionally, the Australia/New Zealand Cadastral Survey Data Model (CSDM), which is a recent development in cadastral surveying, is discussed in section 3.4. The CSDM offers conceptual and implementation options relevant to this research. A high-level mapping with LADM Parts 1 and 2 is presented in sub-section 3.4.2. Finally, section 3.5 provides a summary of the chapter.

3.1 Importance of standardisation

Data interoperability is essential for enabling seamless sharing, integration, and understanding of information across the geospatial and built environment sectors. This is particularly important in managing the lifecycle of spatial units, where data must be reliable, consistent, and traceable across different systems. Key in achieving this are semantic frameworks, standardised data structures, APIs, in the context of data provenance, which help to maintain data consistency and accountability (ISO/TC211, 2023). The impact of non-uniform information models, file formats and software landscapes is addressed through using domain-specific standards, developed to meet the diverse needs of various stakeholders.

Standardisation holds value when widely recognised and implemented. While some standards are well-known and widely adopted, others may be used without full awareness, and their evolving nature means that some have yet to reach their (full) potential. Standards play a critical role in harmonising data across domains, especially when backed by national or international regulations. Through a consensus-driven approach, standards facilitate the integration of geospatial, AECOO domain, within governments, including the European Commission (EC), adopting specific standards that effectively grant them legal or quasi-legal status.

Standardisation bodies, such as the International Organisation for Standardisation (ISO), particularly its Technical Committee 211 (ISO/TC 211), the Open Geospatial Consortium (OGC), and buildingSMART International (bSI), play key roles in developing and establishing international standards for geospatial data and AECOO interoperability. These organisations operate collaboratively and independently to develop high-quality, standards that drive innovation, efficiency and global collaboration. For instance, OGC adopts foundational ISO/TC 211 standards into its Abstract Specifications, ensuring alignment with international frameworks.

In 2024, OGC established the LADM Standards Working Group (SWG), tasked to create implementation support, including encoding standards for all Parts of the ISO LADM, which underscores the commitment to enhancing interoperability across geospatial applications.

Figure 3.1 presents three different levels of standardisation organisations involved in geospatial standardisation, illustrating representation organisations. At the national level, examples of local organisations demonstrate how global standards are adapted and applied to meet specific national requirements.

At the European level, the European Committee for Standardization (CEN) develops standards across various sectors, including the built environment and geospatial domains. CEN not only creates new standards but also adopts international standards to ensure consistency and interoperability across Europe. Additionally, the EU INSPIRE Directive (Infrastructure for Spatial Information in the European Community) significantly contributed to geoinformation standardisation in Europe. By establishing a harmonised framework for spatial data and services, INSPIRE enables effective cross-border data sharing and supports policymaking at all levels of governance, fostering consistency in geospatial information use across member states[11]. On a national level, organisations are responsible for adapting and implementing these standards, ensuring alignment with European and global frameworks. This coordination facilitates seamless geospatial and built environment interoperability across borders.

11 https://knowledge-base.inspire.ec.europa.eu/overview_en

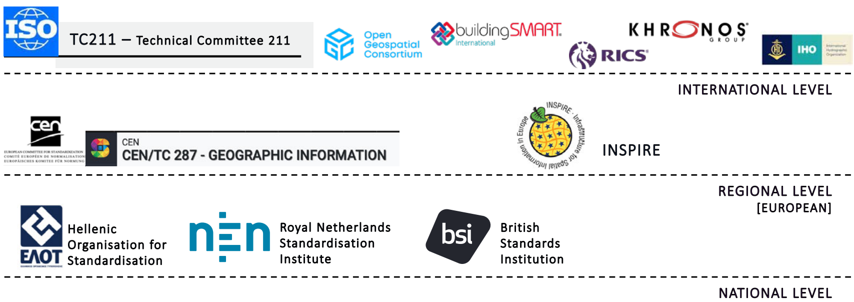

FIG. 3.1 Representative standardisation organisations for geospatial information at international, regional and national level

Additionally, initiatives such as the Minimal Interoperability Mechanisms (MIMs) developed by Open & Agile Smart Cities (OASC) help to promote interoperability, particularly in smart cities and communities. MIMs provide vendor-neutral mechanisms that simplify the alignment of data, systems, and services, assisting municipalities or regions in digital transformation efforts. By identifying Pivotal Points of Interoperability (PPIs) and developing connectors between systems, MIMs have gained traction in real-world applications, increasingly being referenced in requests for proposals and tenders (OASC, 2024).

Open standards are crucial in overcoming the limitations imposed by proprietary information models and formats, fostering a more integrated and efficient workflow across various sectors. By adhering to open standards, stakeholders can ensure that i) data is interoperable across different systems, ii) support consistent data structuring and sharing within the Spatial Development Lifecycle, and iii) avoid being locked into proprietary systems that may limit flexibility. Additionally, open standards contribute to the implementation of FAIR (Findable, Accessible, Interoperable, Reusable) principles, facilitating easier discovery, access, and reuse of data across diverse applications and contexts.

The current landscape of geospatial data sharing and reuse in Europe, as observed by ISO/TC 211 (2023), reflects the achievements and challenges of various data harmonisation frameworks, such as INSPIRE Directive. New data sources, evolving standards, and innovative digital tools have significantly reshaped the environment in which interoperable data sharing operates. Recognising this evolving context, the EC is actively promoting the creation of a single market for data, aimed at securing Europe's global competitiveness and data sovereignty. This initiative involves the establishment of Common European Data Spaces in strategic sectors vital to the economy and public interests, all underpinned by digital-driven initiatives, see: ISO/

TC 211 (2023). To function effectively, these Data Spaces (see Figure 3.2) rely on three fundamental technical pillars: Data Interoperability (with standards playing a key-role); Data Sovereignty and Trust; and Data Value Creation, proposed to be further enriched by the Horizon Europe USAGE project (USAGE, 2024).

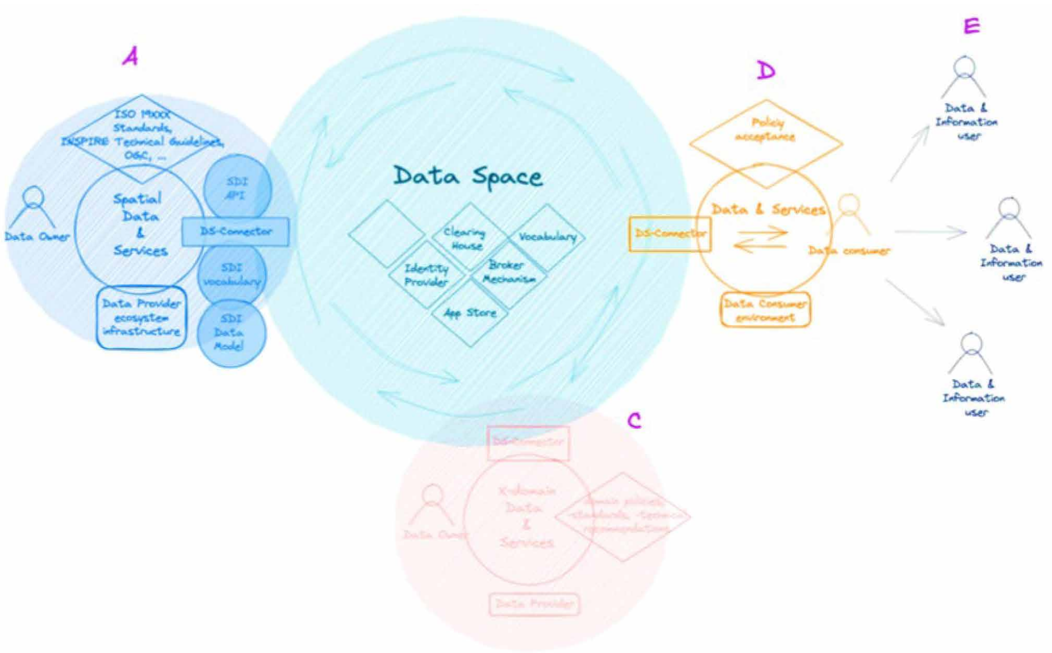

FIG. 3.2 EU Data Spaces from a (Spatial Data Infrastructure) SDI perspective (ISO/ TC211, 2023)

The European Commission's Implementing Regulation 2023/138 (EC, 2022), established under the Open Data Directive, requires public sector bodies to provide High-Value Datasets (HVDs) across six key thematic areas. These datasets, when made available in open and reusable formats, offer economic, social, and environmental benefits. By adhering to standardised and interoperable formats (ISO/TC211, 2023; EC, 2023a), the regulation promotes transparency, drives innovation, and fosters data-driven growth. Among these HVDs are cadastral parcel datasets, which are critical to LA by linking land parcels with ownership rights and supplementary data, such as property values. These datasets enable crucial applications, including disaster response, real estate market operations, environmental protection, and climate change mitigation and adaptation. Furthermore, they underpin fair property taxation systems, contributing to sustainable governance and development.

The cadastral parcel dataset, as mandated under the European Commission's Implementing Regulation 2023/138, aligns closely and can be achieved with LADM. By aligning cadastral parcel datasets with the LADM, public sector bodies can enhance the utility, interoperability, and sustainability of land-related information, meeting both regulatory and international standardisation goals.

In many countries, particularly in those with federated systems, different government entities manage LA and land-use planning data, highlighting the necessity of standardisation for information interoperability. As spatial units move through their lifecycle, -from planning to construction and registration- efficient data exchange and reuse become essential. Global standardisation efforts, led by organisations such as ISO, OGC and FIG have contributed significantly to facilitate cross-border data integration, helping streamline LA processes. Geospatial standards continuously evolve to address the increasing demand for data reuse and interoperability. They increasingly support advanced formats like 3D and 4D (meaning 3D + time) and integrate non-spatial data into comprehensive management systems, such as ISO 19650 series "Managing Information with Building Information Modelling" for BIM. These standards are modular and extensible, designed to manage complex datasets and facilitate seamless data exchange. Frameworks like the New European Interoperability Framework (EC, 2017a) underscore the importance of enhanced interoperability. This evolution is driven by technological advancements, increased digital literacy, and alignment with global initiatives like the UN Integrated Geospatial Information Framework (IGIF) (IGIF, 2023). Collaborative efforts among governments, industries, academia, and international organisations foster that geospatial data remains valuable, driving efficient decision-making and addressing societal challenges across sectors.

The boundaries between the geospatial and built environment domains have traditionally been disciplinary and practically distinct, but advancements in GIS, BIM, and real-time IoT data have increasingly blurred these divisions (OGC, BuildingSmart, 2020). This shift has heightened the need for greater interoperability to support complex decision-making processes such as urban planning, which relies on integrating multiple models and data sources (OGC, BuildingSmart, 2020). The adoption of standards by key stakeholders (responsible for information management in both domains) will have a broad impact across the digital ecosystem of the information community, benefiting numerous user groups, including decision makers, developers, data creators and various, other user groups.

The integration of these domains, termed 'GeoBIM', goes beyond technical aspects such as mapping between data formats and coordinating systems; it involves deeper interpretations of spatial relationships that are embedded in various standards and conceptual models. The evolution of these standards over time is essential to meet the growing demand for comprehensive, interoperable data solutions.

A range of standards that facilitate the description and modelling of elements and interrelationships between the built environment and geospatial domains, facilitating the effective collaboration among stakeholders, such as decision-makers, developers, and data creators within the digital ecosystem, presented in Figure 3.3. Namely:

- **OGC CityGML** for modelling and exchanging 3D city models that describe the geometry, topology, semantics, and appearance of urban environments in various levels of detail (LoD),
- **bSI IFC** for exchanging BIM (further analysed in section 3.2),
- **OGC LandInfra** for the management and representation of civil engineering and land infrastructure elements,
- **LandXML** for representing civil engineering and survey data, particularly in road, railway, and land development projects,
- **OGC IndoorGML** for modelling of indoor spaces and the topological relationships between them,
- **OGC MUDDI** for modelling of underground infrastructure data,
- **ePlan** for exchanging digital cadastral data between land registries and local governments,
- **Cadastral Survey Data Model**, which is under development for the digital exchange of 3D survey data in Australia and New Zealand, and
- **ISO LADM** for modelling people-to-land relationships through RRRs.

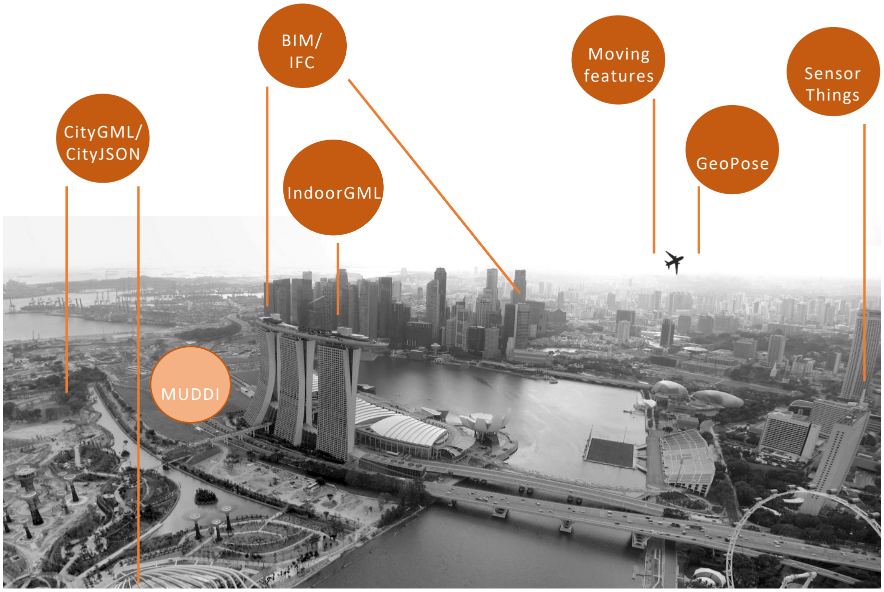

FIG. 3.3 OGC standards in the built environment (OGC, 2024b; adapted)

In the context of this dissertation, four influential and promising standards—IFC, LandInfra, the Cadastral Survey Data Model (CSDM), and LADM—are discussed due to their pivotal roles in enabling information reuse throughout the SDL. Specifically, IFC and LADM are recognised and widely used international ISO standards, LandInfra provides strong documentation on the surveying domain, aligning with the objectives of this research, and CSDM is a promising development aimed at standardisation to facilitate efficient cadastral information exchange between survey professionals and LA agencies. Consequently, the standards briefly introduced earlier are not further analysed. This chapter focuses on IFC, LandInfra, and CSDM, while chapter 4 provides a detailed analysis of LADM and its role in modelling land-related information. It is worth noting that even standards not examined in depth in this dissertation are considered integral to the SDL framework, supporting the research's overarching objective of addressing the critical need for information reuse.

3.2 Building Information Model (BIM) and Industry Foundation Classes (IFC)

Building Information Modelling (BIM) has become a digital innovation for managing buildings and infrastructure. Over the past decade, it has gained global recognition for its ability to create comprehensive digital representations of assets throughout their lifecycle, from design and construction to operation and maintenance. Formally defined by the ISO 19650 series in 2018 and 2024, BIM provides both detailed models and processes that integrate geometric and semantic data, enabling stakeholders across the AECOO sector to collaborate efficiently, throughout the entire lifecycle of any built asset, accommodating projects of varying scales and complexities, as depicted in Figure 3.4.

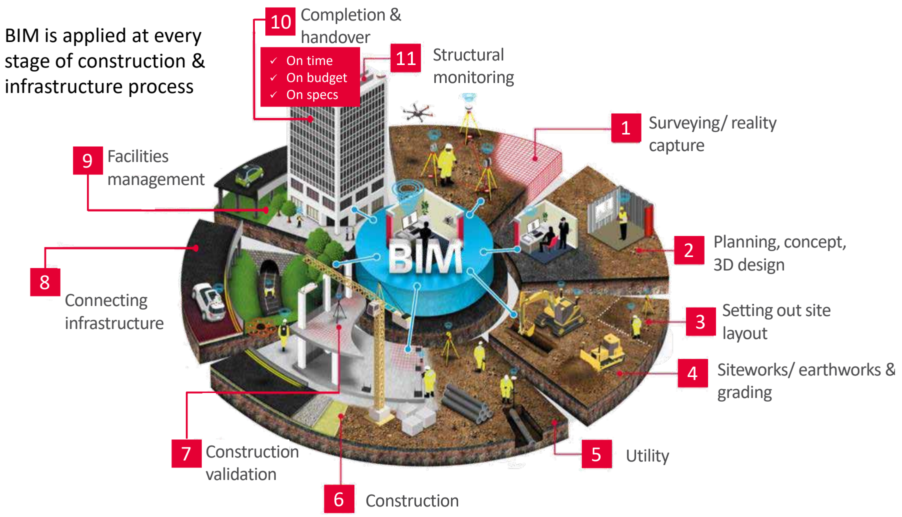

FIG. 3.4 BIM Source: Leica (OGC, 2024c (from Leica Geosystems); adapted)

BIM's universal appeal lies in its ability to facilitate information sharing across multiple software platforms using proprietary data formats, created by specific software manufacturers, and vendor-neutral data that can be accessed and modified by any compatible software (Eastman, 2011; Borrmann et al., 2018; buildingSMART, 2019).

With the growing global adoption of BIM, many governments have developed BIM strategies, and openBIM standards have been embraced to facilitate accessibility and vendor neutrality, despite the different rate of adoption and differing BIM-related regulations across countries and jurisdictions. The global BIM adoption landscape in 2024 (Chudasama, 2024, Figure 3.5) reveals a complex picture, with varying levels of implementation and strategic approaches across regions.

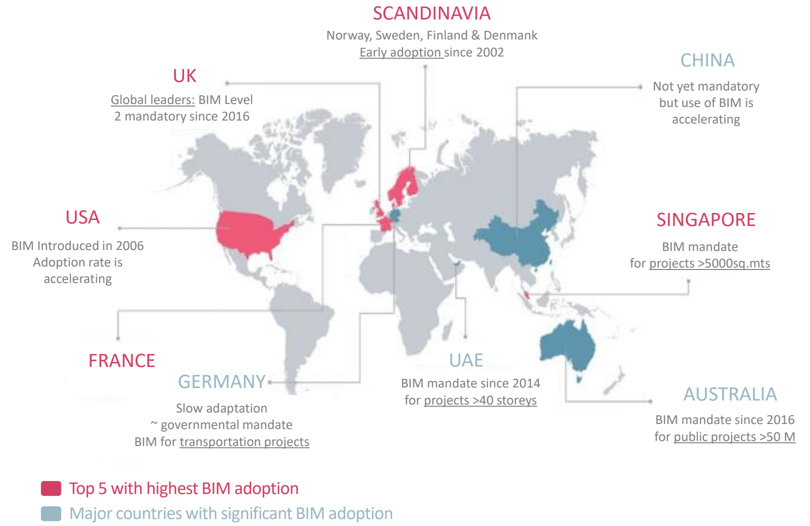

FIG. 3.5 Front runners in BIM adoption in 2024 (Chudasama, 2024, adapted)

To maximise the benefits of BIM and make it accessible to all stakeholders, the buildingSMART alliance introduced openBIM[12], which is vendor-neutral, based on open standards and workflows. openBIM enhances the management, usability, and sustainability of digital data within the AECOO sector by fostering interoperability across project lifecycles. By aligning with ISO 19650 standards, openBIM enables seamless collaboration among all project participants, improving communication and ensuring consistent data quality.

12 https://www.buildingsmart.org/about/openbim/

Key organisations involved in developing BIM standards and protocols include ISO/TC59/SC13 BIM, ISO/TC184/SC4 STEP, CEN TC442 BIM, EU BIM Task Group (EC, 2017b), BuildingSMART Alliance, and OGC. The UK has been a pioneer in BIM implementation, establishing key principles and requirements in 2011, which were later aligned with international standards like ISO 19650. In 2021, the EU BIM Task Group reinforced the importance of openBIM through a position paper to the EU (EU BIM Task Group, 2021). Various professional organisations, including the European Construction Industry Federation (FIEC), Architects' Council of Europe (ACE), and the European Federation of Engineering Consultancy Associations (EFCA), have also stressed the significance of vendor-neutrality and open standards to promote wider BIM adoption across the industry (FIEC, 2020).

To further improve communication and interoperability within the industry, buildingSMART has developed several international open BIM standards,apart from IFC that has already presented, including (buildingSMART, 2019):

- **IFD (International Framework for Dictionaries)/ bsDD (buildingSMART Data Dictionary):** initially developed to provide a framework for managing dictionaries within the BIM context (buildingSMART, 2019). The bSDD has superseded IFD and now functions as an online service that hosts classifications, their associated properties, units, and translations (ISO 19650-1). The bsDD provides a standardised workflow that ensures data quality and consistency by enabling links between all the content inside the database.

- **BCF (BIM Collaboration Format):** is an XML-based format that facilitates communication between systems of stakeholders by enabling the exchange of information related to BIM models (buildingSMART, 2019).

- **IDM/MVD (Information Delivery Manual/ Model View Definitions):** is a BIM methodology designed to capture and specify processes and information flow throughout the lifecycle of a built asset among the various stakeholders (ISO, 2016b). This methodology enhances communication, harmonises object data models, and improves the efficiency of project management by bringing together multiple stakeholders within a project-specific organisation. IDM (voted as ISO 29481-1:2016 and currently being revised and CEN standard) provides a structured approach to specifying information requirements for specific use cases, composed of three main parts: a process map, exchange requirements, and a model view definition (MVD) (ISO, 2016b). MVDs, which facilitate connections between all database contents, can be generated automatically by linking IDM with the bSDD. This integration supports consistent data management and interoperability across the lifecycle of an infrastructure.

- **Information Delivery Specification (IDS):** is machine-readable document that specifies exchange requirements and defines the level of information needed. The “BIM Basis ILS”[13] (IFC Leveraging Specification) is the Dutch BIM based IDS, widely adopted in the industry. It is an application guideline for the structured and unambiguous exchange of information in the built environment, focusing on the construction. It defines general and actionable guidelines on how information should be exported to IFC to make models as unambiguous and useful for reuse as possible. Currently, the second version of this application guideline has been released, which builds on the previously laid foundation and is supplemented with feedback and insights from the work field.

- **Construction Operation Building Information Exchange (COBie):** is a non-proprietary data format that allows resource data sharing rather than geometric data and it is used to transfer data and documents created during design and construction to end users (buildingSMART, 2019).

Figure 3.6 illustrates the complementary relationships among three key buildingSMART standards—bSDD, IFC, and IDM. It highlights how these standards collectively support the digital construction process. bSDD defines the terminology and semantics (“what” of the data), IFC provides a digital structure for interoperability (“how” data is shared), and IDM specifies and clarifies processes (“which” data and when it is used). Together, these standards enable seamless data exchange and collaboration across various stages of the construction lifecycle.

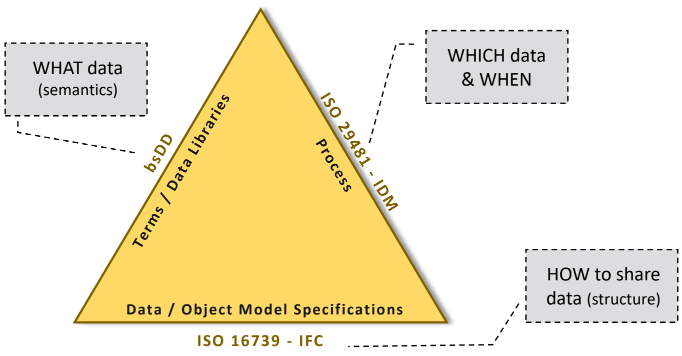

FIG. 3.6 Relationships between OpenBIM standards (buildingSMART, 2019; adapted)

13 https://www.digigo.nu/en/ilsen-en-richtlijnen/bim-base-ids/

The IFC, voted as ISO 16739-1:2024 (ISO, 2024), is a vendor-neutral and platform-independent data model, designed to facilitate data consistency and interoperability between various representations and design decisions in the construction and asset management industries. It enhances collaboration among stakeholders—such as architects, engineers, and contractors—by functioning as both a file format and a comprehensive data model standard.

The IFC schema provides a structured set of rules and definitions for representing building data, encompassing entities like walls, doors, and spaces, along with their relationships, to maintain consistent syntax and semantics across various software platforms. The EXPRESS schema of IFC[14] generates XML schemas (XSD) to describe processes related to installation, construction, and operation. While IFC is commonly encoded in the STEP Physical File (.ifc)[15] format, other formats like XML and JSON are also supported, depending on software compatibility and project needs. Its hierarchical structure allows for a well-organised representation of interconnected building components, facilitating efficient and seamless data exchange.

14 https://standards.buildingsmart.org/documents/Implementation/The_EXPRESS_Definition_Language_for_IFC_Development.pdf
15 https://technical.buildingsmart.org/standards/ifc/ifc-formats/

3.3 OGC LandInfra and InfraGML

The Land and Infrastructure Conceptual Model (LandInfra) standard developed by the OGC (OGC, 2016) serves as a successor to LandXML, which is an XML-based open data model primarily used for representing civil engineering and survey measurement data (LandXML, 2016). While retaining the core functionalities of LandXML, LandInfra enhances its capabilities by implementing the data model in GML -through InfraGML- and describing it using a UML conceptual framework. The various aspects modelled in LandInfra are illustrated in Figure 3.7.

A standout feature of LandInfra is its Survey package, which is specifically designed to model surveying-related information essential for representing the location data of infrastructure. It encompasses sub-packages to manage survey observations, survey equipment, and the results of surveying processes, refining the generic standard Observations & Measurements (ISO 19156:2023) (ISO (2023). The Survey package facilitates the recording, reprocessing, and documentation of survey observations, ensuring that all fieldwork is controlled, corrected, and archived according to the necessary regulations.

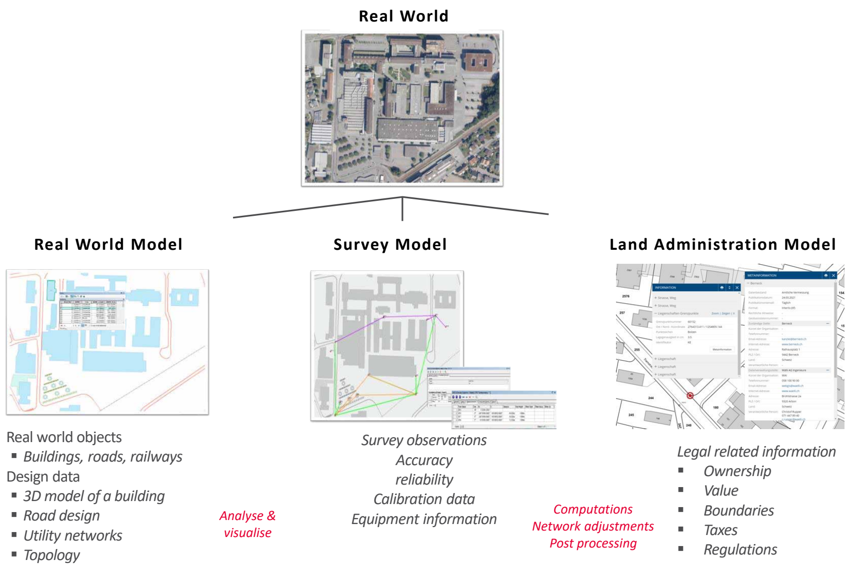

FIG. 3.7 Real world object modelled using LandInfra components (OGC, 2024c; adapted)

In addition, the LandDivision package plays a crucial role in managing information about land divisions. It provides the framework for delineating parts of the land surface through existing and new boundaries, which are critical for defining ownership and other land-related rights. This package supports fieldwork activities by marking of boundaries, ensuring that the land division process and the collected data are consistent and legally sound.

Together, these packages within LandInfra enable the seamless integration of surveying data within the broader context of land and infrastructure management processes. This approach allows both the physical and legal dimensions of land use to be accurately represented and maintained throughout the project's lifecycle. Such integration is critical for upholding the accuracy and interoperability of land and infrastructure data across various applications, including urban planning, construction, and LA. InfraGML, the GML-based encoding of the LandInfra data model, plays a pivotal crucial in promoting interoperability and data integration (Figure 3.8).

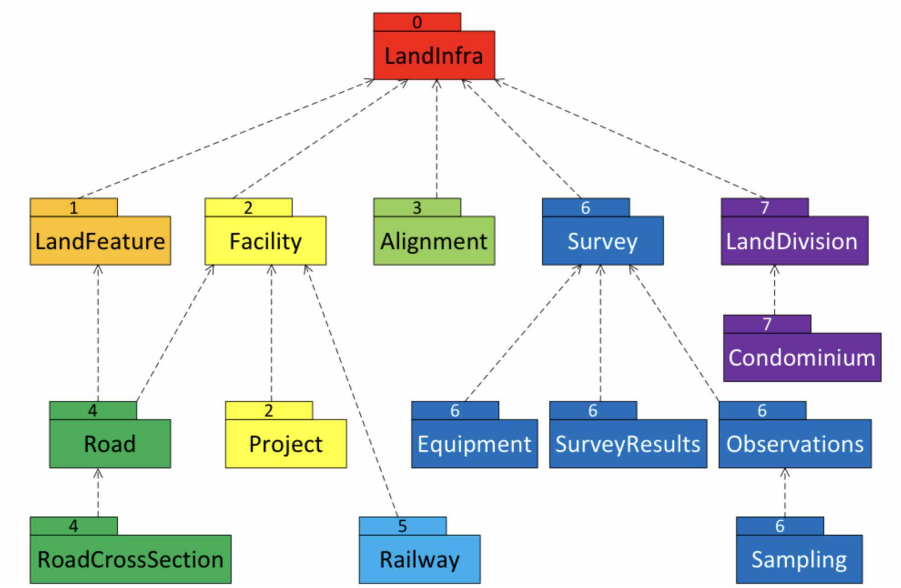

FIG. 3.8 InfraGML Parts (boxes present the alignment with Figure 3.7) (OGC, 2017, adapted)

LandInfra's application extends beyond surveying to sectors like urban facility management, and urban planning. When integrated with other OGC standards, such as CityGML, it supports various urban applications, including environmental assessments like noise exposure and solar irradiation analysis. Unlike CityGML, LandInfra explicitly models the materials of infrastructure elements (e.g., road surfaces, terrain, railways). This makes LandInfra a comprehensive and versatile standard for managing and integrating land and infrastructure data across various sectors (Kavisha, 2020).

Despite these challenges, LandInfra holds significant potential, particularly through its detailed Survey package (Part 6), which aligns with other standards like LADM. Both LADM and LandInfra share overlapping and complementary scopes, especially in surveying, land parcels, and apartments. Several studies (e.g., Çağdaş et al., 2016; Kalogianni et al., 2021b; Kara et al., 2018a; Lemmen et al., 2017) highlight the synergy between the two standards, emphasising the need for collaboration between standardisation bodies such as ISO TC211 and OGC. The refinement of the LADM survey model based on LandInfra and the establishment of a Standards Working Group (SWG) involving LandInfra developers underscore ongoing efforts to integrate and harmonise these standards. These initiatives aim to improve interoperability and information reuse in LA and infrastructure, ensuring that modern standards meet the evolving demands of these sectors.

During the OGC Spring 2024 Members' Meeting in Delft[16], discussions centred on the current state and future of the LandInfra standard, highlighting its limited adoption despite being a comprehensive standard for civil engineering and land infrastructure. The persistence of the older LandXML standard, widely supported by vendors and deeply integrated into industry workflows, has created minimal motivation for stakeholders to transition to LandInfra. However, LandXML has significant limitations, including weak governance and fragmented implementations. Its lack of a conceptual model exacerbates interoperability challenges, making it unsuitable for modern applications like the 3D CSDM (which is further analysed in section 3.4). In contrast, LandInfra offers more robust governance through the OGC, alignment with contemporary technological standards, and compatibility with BIM and GIS. These features position LandInfra as a more reliable and future-oriented standard, reducing governance burdens and offering greater interoperability.

16 https://www.ogc.org/ogc-events/128th-ogc-member-meeting-tu-delft/

The resistance to adopting LandInfra reflects a broader issue in the geospatial and infrastructure sectors, where stability and compatibility often take precedence over the adoption of new standards, unless they offer immediate, clear advantages. The discussions at the OGC meeting[17] underscored the need for compelling benefits in functionality, interoperability, and support for emerging technologies to drive industry transition to LandInfra. Overcoming this resistance will require strong support from government agencies, industry leaders, and software vendors, along with a robust ecosystem of compatible tools and demonstrable value.

Despite these challenges, LandInfra holds significant potential, particularly through its detailed Survey package (Part 6), which aligns with other standards like LADM. Both LADM and LandInfra share overlapping and complementary scopes, especially in surveying, land parcels, and apartments. Several studies (e.g., Çağdaş et al., 2016; Kalogianni et al., 2021b; Kara et al., 2018a; Lemmen et al., 2017) highlight the synergy between the two standards, emphasising the need for collaboration between standardisation bodies such as ISO TC211 and OGC. The refinement of the LADM survey model based on LandInfra and the establishment of a Standards Working Group (SWG), involving LandInfra developers, underscore ongoing efforts to integrate and harmonise these standards. This is expected in the context of LADM's second edition and specifically in Part 2 – Land Registration (already adopted as ISO19152-2:2025, (ISO, 2025a)) and Part 6 – Implementation (as further discussed in sub-section 4.2.2). These initiatives aim to improve interoperability and information reuse in LA and infrastructure sectors, ensuring that standards meet the evolving demands of these sectors.

17 https://www.ogc.org/ogc-events/128th-ogc-member-meeting-tu-delft/

3.4 ICSM Cadastral Survey Data Model (CSDM)

The Cadastral Survey Data Model (CSDM), developed by the Intergovernmental Committee on Surveying and Mapping (ICSM), is a candidate for an Australia/New Zealand cadastral survey standard. It is designed to facilitate the transition from traditional 2D paper-based cadastral systems to fully digital 3D models, aligned with OGC Abstract Specification (ICSM, 2023).

The ICSM 3D Cadastral Survey Data Model and Exchange Project developed a new standard specification to support the efficient exchange of cadastral information between survey professionals and land administration agencies or land registries in Australia and New Zealand.

This model is critical as cadastral surveyors face the challenge of integrating 3D models of property and other legal boundaries into modern digital environments. In parallel, the Cadastre 2034 strategy developed by ICSM envisions a digital future for LA in Australia, supporting the integration of digital twins, smart cities, planning, and utility management, all of which will be increasingly underpinned by the CSDM.

These drivers are pushing the modernisation of LAS, making it possible to fully digitise the exchange of LA-related data. This standard is expected to enable surveyors to shift from submitting paper or PDF plans to sharing fully digital datasets that incorporate 3D elements.

The following sub-sections discuss the current implementation status of 2D and 3D CSDM (sub-section 3.4.1), concluding with a high-level mapping of the 2D CSDM implementation and LADM Edition II Parts 1 and 2 (sub-section 3.4.2).

3.4.1 2D and 3D Cadastral Survey Data Model implementations

The ICSM has developed the conceptual model of the 3D CSDM (by the private sector surveyors to the authorities) to standardise and enhance the quality of 3D cadastral data submissions. This model includes a formal conceptual and linked logical data structure designed to meet the requirements derived from current and emerging standards in the geospatial and online technology sectors. The model builds on proven implementation pathways, allowing for the integration of cadastral data across various jurisdictions.

The CSDM accommodates jurisdictional differences through profiling. Currently, four implementation profiles have been developed, employing the OGC Building Blocks[18] methodology which provides a common platform for developing and testing reusable schemas and profiles. These profiles cover New Zealand, Victoria, Western Australia, and the ICSM Aus/NZ Common Profile. Each profile builds upon a common CSDM model, extended it with specific constraints and vocabularies, ensuring both flexibility and consistency.

Figure 3.9 shows the relationships between these jurisdictional profiles and the underlying common model.

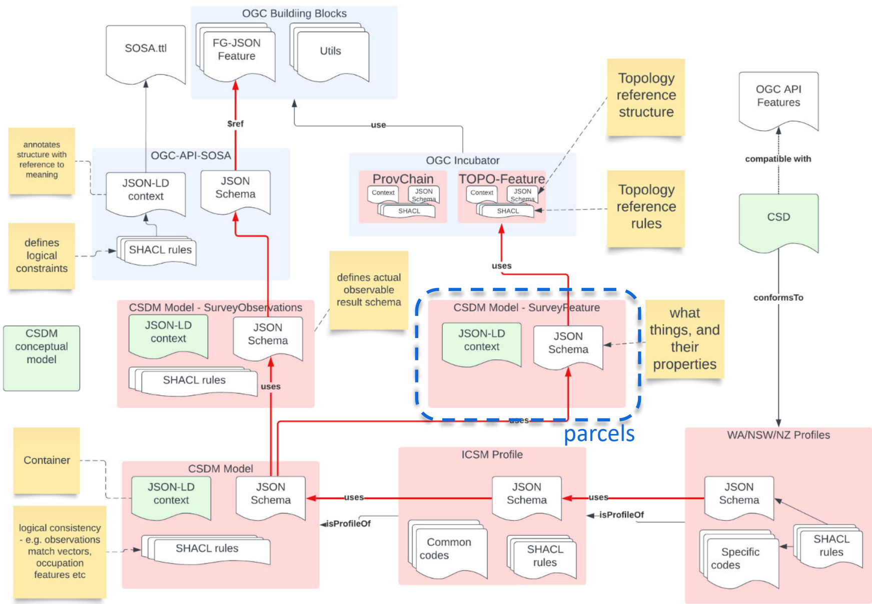

FIG. 3.9 Overall Architecture of the CSDM model and relationships with the jurisdiction profiles and OGC technological advances (ICSM, 2023)

18 https://github.com/opengeospatial/bblock-template/blob/master/USAGE.md

In Figure 3.10 the profile for New Zealand is presented.

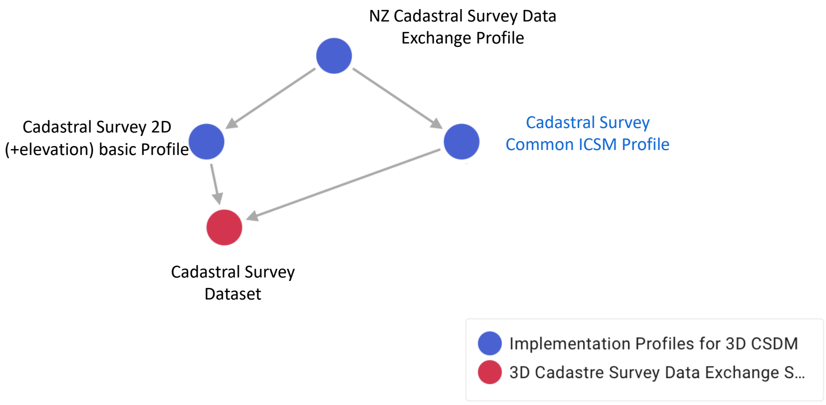

FIG. 3.10 New Zealand Cadastral Survey Data Exchange Profile (ICSM, 2023)

The 2D CSDM implementation uses a variety of encodings including JSON, JSON-LD, GeoJSON, and JSON-FG, all derived from the conceptual CSDM model. The exchange schema is machine-readable, modular, and based on JSON schema, compatible with OGC API Features, facilitating seamless integration with existing systems. These technologies enable efficient data exchange for 2D cadastral survey data, mapping local and regional vocabularies to the CSDM. Moreover, the implementation incorporates a semantic model, which allows additional constraint rules to be specified using the SHACL (Shapes Constraint Language) standard[19] (for instance, constraints to check that the parcel's geometry is valid).

To further enhance the 2D implementation, GeoJSON (Butler et al., 2016) and Features and Geometries JSON (JSON-FG) (OGC, 2023) adds geometric capabilities. However, while GeoJSON currently supports several geometry types, it does not officially support 3D geometries. The OGC JSON-FG Standards Working Group has proposed extending GeoJSON to include 3D geometries (OGC, 2023), addressing a gap for the future development of 3D CSDM.

The 3D CSDM implementation focuses on defining spatial geometries and spatial functions necessary for 3D cadastral parcels to be valid and topologically sound. This is crucial for dealing with the complexities inherent in cadastral datasets, such as non-convex geometries and the intersections of 3D parcels.

19 https://www.w3.org/TR/shacl/

3.4.2 2D Cadastral Survey Data Model and ISO 19152 LADM

The 2D CSDM has been mapped to Parts 1 and 2 of Edition II of LADM, providing a high-level alignment of major elements (ICSM, 2023). Upon initial examination, the CSDM classes generally align well with those in LADM, with only a few exceptions, such as the Occupation Marks and Occupation Features (representing a set of feature descriptions for occupation evidence, supporting the use of multiple collections of features sourced from other systems)[20], which do not have a direct counterpart in the LADM structure.

Specifically, it illustrates a conceptual model that integrates surveying and representation elements, feature types, and observations while maintaining compatibility with LADM standards.

The high-level mapping between LADM (right side, classes in blue colour) and CSDM (left side, classes in green colour) is presented in Figure 3.11 and Figure 3.12. An approach to ensure CSDM alignment with the ISO standard is presented, which is crucial for interoperability and consistency in cadastral survey data management. In many cases, the mapping is a one-to-one match. CSDM Parcels can efficiently map to LA_SpatialUnit (Figure 3.12). In the 2D CSDM, a parcel is defined as a polygon, while in LADM, an LA_BoundaryFace is defined as a face, the 3D more generic counterpart of a polygon. Both models define boundaries (LA_BoundaryString/ observedVectors respectively) as curves (ISO, 2024). What is more, LADM Part 2 models the various survey observation methods through specialised classes, the sub-classes of LA_SurveySource. At the other side, the CSDM vectorObservations element is agnostic and uses the SOSA ontology (Sensor, Observation, Sample, and Actuator) (W3C/OGC, 2017), allowing the same pattern for various observation types.

20 https://icsm-au.github.io/3D-csdm/docs/#Modules-Dependency-Diagram

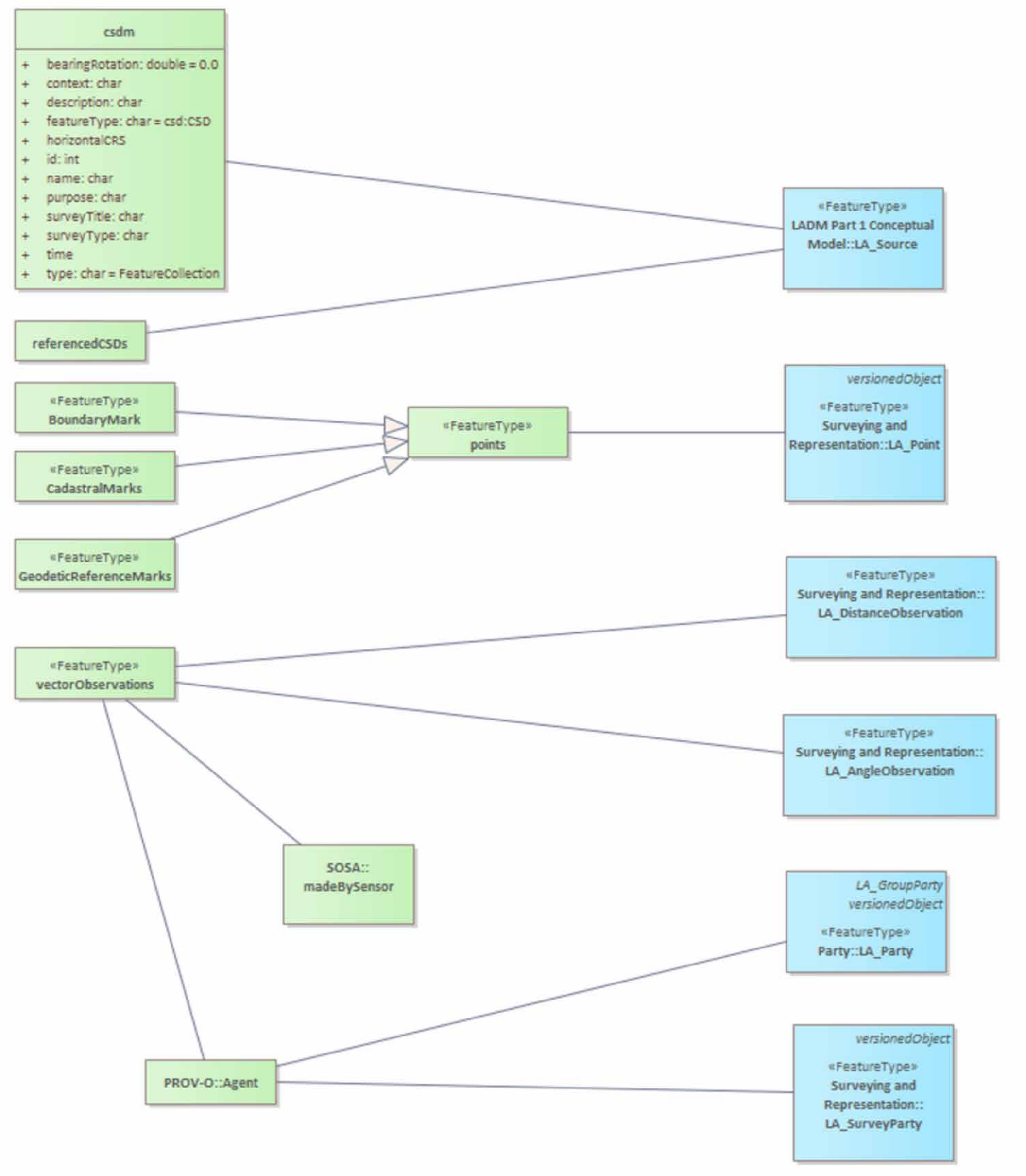

FIG. 3.11 High-level mapping of the major elements of the 2D CSDM JSON encoded implementation has been mapped to Parts 1 and 2 of Edition II of ISO 19152 (ICSM, 2023) -1

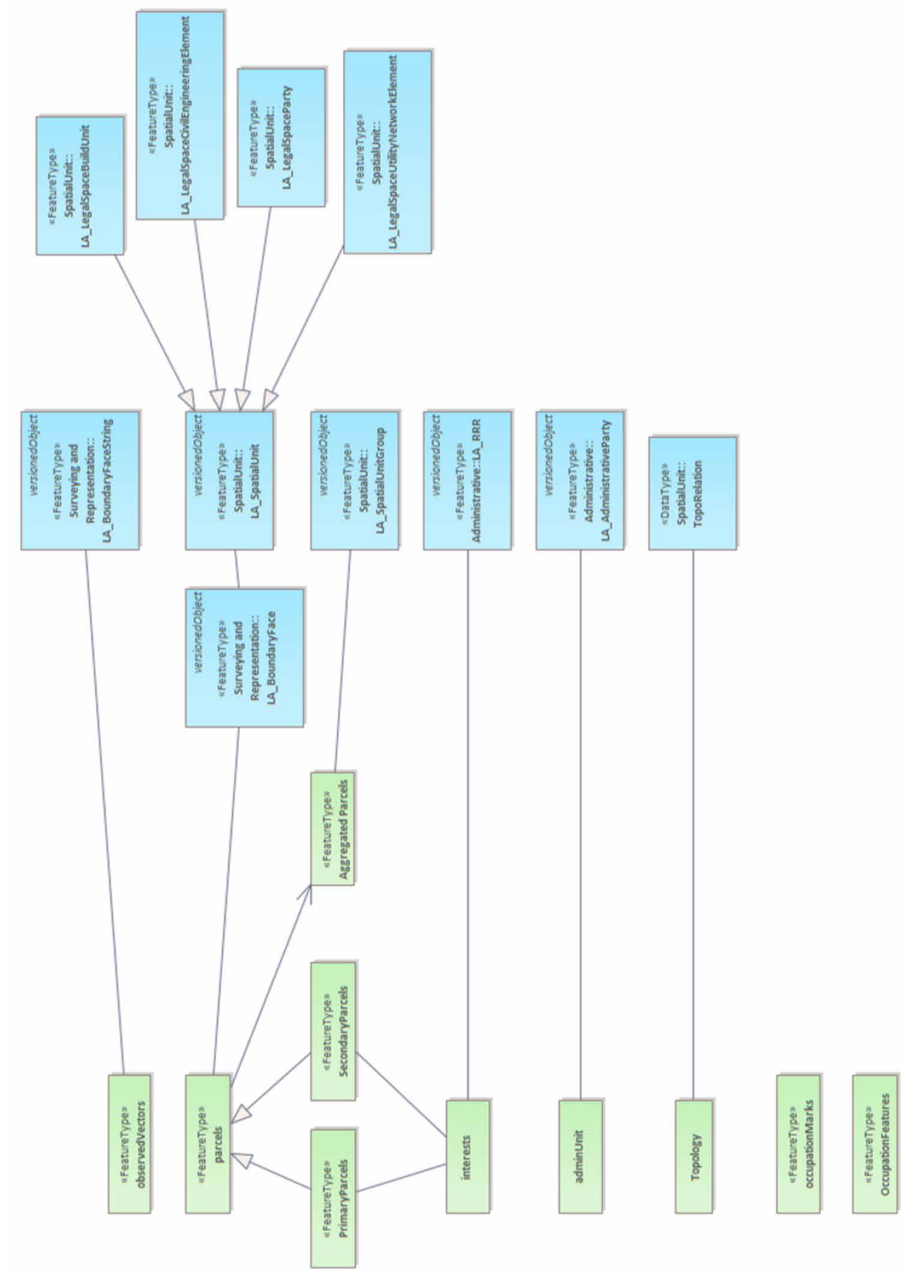

FIG. 3.12 High-level mapping of the major elements of the 2D CSDM JSON encoded implementation has been mapped to Parts 1 and 2 of Edition II of ISO 19152 (ICSM, 2023) -2

Figure 3.13 illustrates the ICSM Equipment vocabulary, showing its correspondence with various LADM Observation Classes.

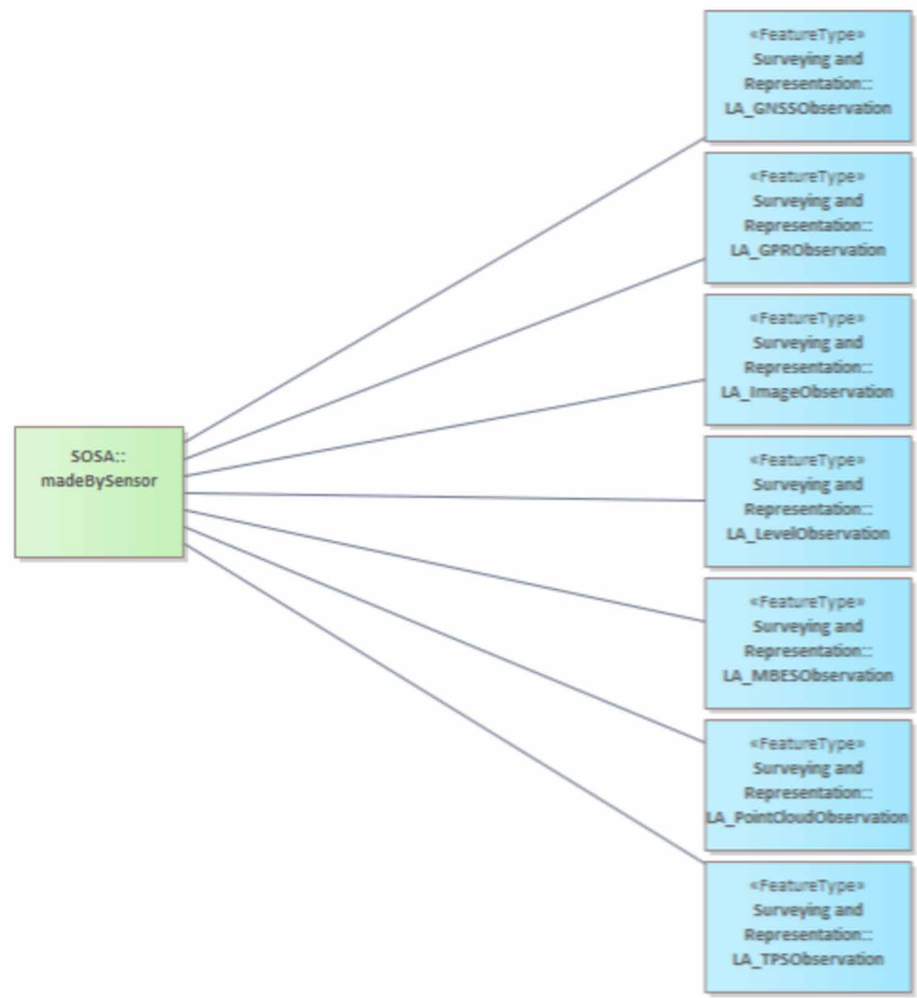

FIG. 3.13 Association between the ICSM Equipment vocabulary and the LADM Part 2 sub-classes of the LA_SurveySource class

3.5 Summary

To answer **Sub-RQ2 “Which standards can support data reuse in the context of SDL, particularly in the context of 3D LA?”**, this chapter delves into the evolving landscape of standardisation in geospatial information management, particularly within the built environment, focusing on standards governing data creation, management, and exchange in surveying and design data of LA. It highlights the challenges of integrating AECOO data with geospatial and economic data, especially concerning consistent data reuse and high-quality data management throughout the Spatial Development Lifecycle. The chapter stresses the critical role of vendor-neutral, standardised data models and formats in achieving data interoperability, reuse, and integration, which are essential for complex processes such as 3D LA and urban planning.

While collaborations among standardisation bodies exist, the proprietary nature of many tools often limits scalability and creates silos within different ecosystems, namely: the geospatial, AECOO and LA. Open standards offer solutions to these challenges by promoting accessible and widely usable frameworks that facilitate collaboration and data accessibility across different platforms and systems. The chapter emphasises the shift from merely unlocking data to enhancing its reusability, exemplified by the evolution from “open data” to “FAIR data” (Findable, Accessible, Interoperable, Reusable). Standards can be made binding by including them into national Laws, European Directives (such as INSPIRE), requests for proposals, tenders or contracts, or they can serve as non-binding policy components to support the continuous improvement of a legal and policy framework for the management of the information at the geospatial and the AECOO domain. Currently, a wide range of standards exists for 2D and 3D geospatial information, as well as building-related data, each developed for specific purposes.

As urbanisation accelerates, BIM adoption is increasing globally, with international standards like IFC leading in data exchange. IFC, supported by bSDD (for semantics) and IDM (for workflows), enhances collaboration, data reuse, and project lifecycle management in infrastructure development. Simultaneously, the OGC’s LandInfra standard, which integrates LA and cadastral surveying data, faces challenges in gaining widespread industry adoption. The reluctance is often driven by the fact that businesses are resistant to change unless it provides immediate, clear benefits over existing, functioning systems. inconsequently there is uncertainty about LandInfra’s future impact. Despite this, LandInfra’s concepts have been integrated into Part 2 of the LADM, demonstrating its potential value for future data interoperability and standardisation.

This chapter examines the role of standards like BIM, IFC, and LandInfra in enhancing data integration and exchange across systems and stakeholders, particularly within urban planning and infrastructure management. It discusses the development of the CSDM in Australia and New Zealand, which aims to bridge gaps between surveying practices and legal requirements while aligning with global standards like LADM. The high-level mapping of CSDM to LADM underscores ongoing efforts to harmonise standards for improved interoperability and information reuse.

The chapter also highlights the CSDM's focus on 3D, showcasing its implementation based on the JSON-FG (OGC, 2023) proposal. This proposal introduces new 3D geometry types—such as Polyhedron, MultiPolyhedron, Prism, and MultiPrism—offering enhanced representation of 3D cadastral parcels. However, support for non-linear primitives, including curves, B-splines, and 3D Non-Uniform Rational B-Splines (NURBS), is still lacking.

Finally, the chapter anticipates that ICSM will seek OGC adoption of this standard, promoting its widespread use in cadastral surveying software. This aligns with advancements in the OGC LADM Standards Working Group, established in June 2024, which aims to support the evolution of standards for improved cadastral and LA practices.

The chapter concludes by emphasising the importance of continued collaboration among governments, academia, and industry to ensure that geospatial data effectively supports decision-making and addresses societal needs across multiple sectors, as the current situation is far for being truly interoperable.

4 The Land Administration Domain Model [LADM]

[Sub-RQ1b] **What is the current state-of-the-art in standardisation in (2D and 3D) Land Administration around the world, as progressed by standardisation organisations?**

[Sub-RQ4a] **Which are the cadastral surveying requirements?**

This chapter is based on the following publications:

*Kara, A., Lemmen, C.H.J., Oosterom, P.J.M., **Kalogianni, E.,** Alattas, A., Indrajit, A. (2024). Design of the new structure and capabilities of LADM Edition II including 3D aspects. Land Use Policy, 137, 107003.*

***Kalogianni, E.,** Janečka, K., Kalantari, M., Dimopoulou, E., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., Govedarica, M., Lemmen, C.H.J., van Oosterom, P.J.M. (2021). Methodology for the development of LADM country profiles. Land Use Policy, 105, 105380.*

ABSTRACT

As described in the previous chapters, the different functions of LA have long existed without an internationally standardised model to support their development and implementation. The LADM, formalised as ISO 19152:2012, addresses this gap of interoperability, as well as systems' evolution and by standardising LAS globally, accommodating diverse and often fragmented cadastral and land registry systems. LADM's flexibility allows to integrate the administration of different forms of tenure, ranging from formal, legally recognised tenures to socially recognised customary rights. To address informal and customary tenure relationships, STDM was developed by UN-Habitat, as a specialisation of LADM. Together, LADM and STDM offer comprehensive solutions for representation of formal and informal land rights in a LAS, promoting better governance and sustainable development in diverse socio-economic settings. The need for a universal standard to improve communication and data exchange among LASs and organisations within a country led to the development of LADM. It offers a standardised framework for recording and managing land-related

information. Subsequently, numerous LADM-based country profiles and STDM implementations, have been developed around the world, along with industry solutions supporting both models. In response to requests from the international LA community, LADM Edition II expands on the first edition. It refines its scope to include land value, use, and development, as well as explicitly addressing marine georegulation while ensuring backwards compatibility with Edition I.
This chapter provides an in-depth exploration of LADM, segmented into three key sections: 4.1 introducing key concepts and structure of LADM Edition I. Section 4.2 briefing LADM Edition II, from the requirements that form the basis for the revision, till the presentation of the various Parts. Section 4.3 provides an overview of the LADM-related developments, organising them into country profiles and software solutions to illustrate practical applications and adaptations of LADM worldwide. The chapter concludes with a summary that highlights the importance of these developments in advancing LA practices globally (section 4.4).

4.1 ISO 19152:2012 LADM Edition I

Whilst there are differences between cadastral and land registry systems across various countries and jurisdictions, a common set of components can typically be observed within LAS. These components include general concepts describing the legal, organisational and technical aspects of LA, which are universally applicable. Key data categories encompass information about parties (people and organisations); Rights, Restrictions and Responsibilities (RRRs) and the basic administrative units where RRRs apply. Additionally, spatial units (parcels, and the legal space of buildings and utility networks); as well as spatial sources (mainly surveying and design), and spatial representations (geometry and topology) are integral to these systems (Lemmen, 2012).

In this sense, the critical factor is how a country or jurisdiction formally defines and organises the set of legally and legitimate recognised rights, right holders and spatial units and, where appropriate, the restrictions and responsibilities arising from public and private law. Therefore, standards in LA are essential to establish a common framework that governs data acquisition, ongoing data management and maintenance and information exchange. This framework is essential not only for maintaining and validating the integrity and accuracy of data, but also for enabling seamless interaction between different systems and stakeholders within and across countries. Adhering to these standards, it can be assured that data is robust, comparable, and usable not only for LA purposes, but across various applications and phases of the Spatial Development Lifecycle (SDL).

TOC

In the early 2000s, growing demand for a standardised model in LA, driven by principles from 'Cadastre 2014' (Kaufmann et al., 1998) and evolving land policy needs, led to the development of the Core Cadastral Domain Model (CCDM). The CCDM aimed to create a unified framework for cadastral data, enabling interoperability across jurisdictions. It introduced foundational concepts that were later refined into the LADM, formalised as ISO 19152:2012. The LADM adopts the definition of LA from the Land Administration Guidelines by UNECE (UNECE, 1996), which broadly defines LA as the "*process of determining, recording and disseminating information about the relation between people and land*" (ISO, 2012), encompassing geographical spaces on, above, and below the surface. Its development, guided by user requirements (Lemmen, 2012), reflects a comprehensive response to global needs in the LA domain.

LADM supports the integration of different forms of tenure, including formal and customary types of tenure, informal tenure and overlapping claims on land[21] and supports the concept of the "*continuum of land rights*" as presented in section 2.1. LADM includes the top-level classification of RRRs, embracing both formal and informal ones, which are reflected in 3 legal profiles for RRRs as included in Annex F of the standard.

As described by Kara et al. (2023c) the LADM and its specialisation, the Social Tenure Domain Model (STDM), are applicable in relation to the implementation of relevant parts of international guidance documents. These include the New Urban Agenda (UN, 2016), the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security (FAO, 2012), UN-HABITAT's Secure Land Rights for All (UN-HABITAT, 2008), the UN-GGIM Expert Group on Land Administration and Management's Framework for Effective Land Administration (FELA). A reference for developing reforming, renewing, strengthening, modernizing, and monitoring LA (UN-GGIM, 2019) and Fit-for-Purpose Land Administration: Guiding principles for country implementation (UNHabitat/ GLTN/ Kadaster, 2016).

Specifically, the UNGGIM FELA notes that "*availability, accessibility, and interoperability of the land data are also necessities for effective land administration. LADM ISO 19152 (Land Administration Domain Model) and IHO S-121 (Maritime Limits and Boundaries) provide starting points for creating these qualities*" (UN-GGIM, 2020). Similarly, the Fit-for-Purpose land administration (FFPLA) guidelines emphasise that "*in order to assure an easy and adaptable interoperability layer with other stakeholders, the data model chosen for the FFP Land Administration system should be based on (ISO 19152:2012) - Land Administration Domain Model (LADM) and the derived Social Tenure Domain Model (STDM)*" (FIG/ World Bank, 2013).

21 https://fig.net/organisation/networks/standards_network/ladm.asp

Moreover, the Addis Ababa Declaration on Geospatial Information Management towards Good Land Governance for the 2030 Agenda states the need to "*develop and agree on a set of fundamental geospatial information elements for land governance as a subset of the UN-GGIM fundamental data themes aligned with the SDG global indicator framework, taking into account the ISO 19152 Land Administration Domain Model and progress in multi-dimensional cadastre and city models*" (UNGGIM, 2016).

These references in international guiding documents align well with the implementation of the SDGs, as detailed in section 2.2. The integration of LADM into global frameworks underscores its critical role in promoting effective and equitable LA practices worldwide.

The rest of this section provides a comprehensive overview of the foundational elements of the LADM as established in its first edition. Sub-section 4.1.1 delves into the core concepts and classes that form the backbone of LADM. Sub-section 4.1.2. explores the 3D functionalities supported by LADM Edition I, while sub-section 4.1.3 introduces the Social Tenure Domain Model (STDM), which is designed to support pro-poor LA.

4.1.1 LADM Edition I concept and core classes

The ISO 19152 LADM (ISO, 2012) has been developed and is maintained by ISO / TC 211 Geographic Information/ Geomatics. This development was initiated by the International Federation of Surveyors (FIG), as part of the developments within the FIG Standards Network and Commissions 3 "Spatial Information Management" & 7 "Cadastre and Land Management". The European Committee for Standardisation (CEN) Technical Committee for geographic information, CEN/TC 287 also adopted the standard (SIST EN ISO 19152:2012).

It is important to note that in this thesis, the term "LADM Edition II" is used to refer to the second edition of the ISO 19152 LADM standard, following ISO 19152:2012. However, ISO follows a different naming convention, where each LADM Part introduced for the first time is officially referred to as the first edition of that specific part. This means that while the overall standard is evolving as a second edition, individual parts are technically considered first editions under ISO's publication framework.

The LADM is one of the first spatial domain-specific standards designed to facilitate standardisation within the LA sector. This further standardisation is needed to capture the semantics of the domain, building upon the agreed foundation of basic standards for geometry, temporal aspects, metadata, as well as observations and measurements from the field (Lemmen et al., 2015). Unlike prescriptive standards, LADM is descriptive and provides a shared ontology for LA, enabling the communication between the involved parties within one country or across diverse jurisdictions. It focuses on the RRRs affecting land (or water), and therefore their geometry.

Although LADM is a conceptual standard, it supports software development (via the model-driven architecture (MDA)), facilitates seamless data exchange, interoperability, and quality management within distributed LASs, thus promoting efficiency and collaboration in LA practices worldwide (Kara et al., 2023a). It also accelerates the implementation of proper LAS that will support sustainable development (Lemmen et al., 2020).

LADM serves as a cornerstone in global LA and Spatial Information Infrastructure (van Oosterom et al., 2009) as it functions as a universal framework, defining terminology for LA, based on various national and international systems that is as simple as possible to be useful in practice. The terminology allows a shared description of different formal or informal practices and procedures in various jurisdictions (ISO, 2024). The standard further provides a basis for national and regional profiles, sound examples of these are presented in section 4.3. LADM has been developed with the principle of using existing standards wherever possible for sustainable and interoperable data management, as presented by Kara et al. (2023c).

Three packages, namely Party, Administrative, and Spatial Unit, and one sub package, Surveying and Representation, constitute the conceptual schema of LADM (Lemmen et al. 2015), see Figure 4.1 for the representation in Unified Modelling Language (UML). The Party package (illustrated with green colour) includes information about parties, which refer to persons, groups of persons or legal persons, that make an identifiable single (legal) entity, representing legal and natural people.

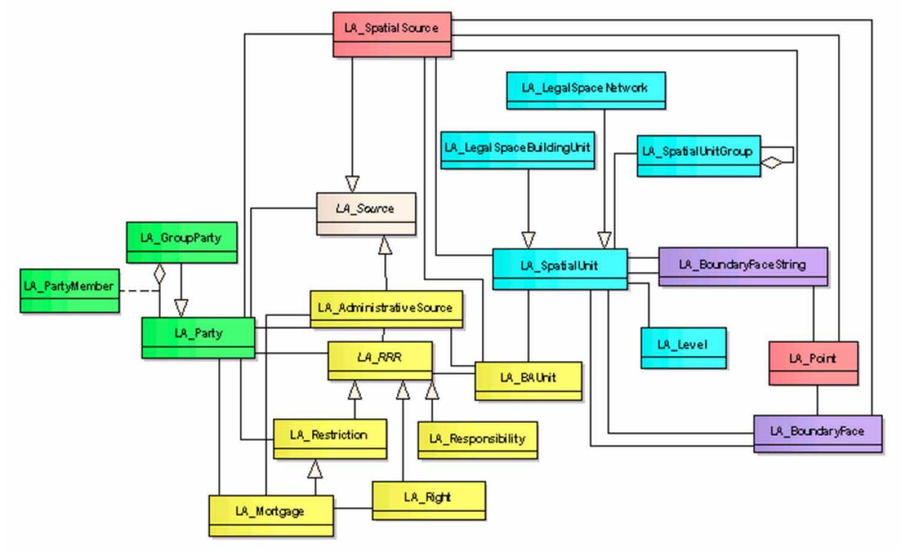

FIG. 4.1 Overview of LADM Edition I classes (Lemmen et al., 2015a)

The Administrative package (depicted in yellow) pertains to the RRRs associated with basic administrative units within LA. A right represents an action, activity, or set of activities that a system participant may undertake concerning a resource. These rights can overlap or conflict (Lemmen et al., 2015a). Restrictions and responsibilities, conceptually linked to rights, reflect the dual nature of relationships between right holders and landowners through land. From the landowner's perspective, rights held by third parties are experienced as either responsibilities or restrictions (Kalogianni et al., 2022a).

LADM (ISO, 2012) defines restrictions (Clause 4.1.19) as formal or informal obligations to refrain from certain actions, whereas responsibilities (Clause 4.1.18) are formal or informal obligations to perform specific actions. Conceptually, restrictions can be understood as rights held exclusively by third parties, excluding the landowner's enjoyment of these rights. Responsibilities, on the other hand, are rights granted to third parties in a non-exclusive manner.

This dynamic can also be framed in terms of "negative rights" and "positive rights" (Kalogianni et al., 2022a). Negative rights enable third parties to benefit from land owned by someone else (e.g., easements), while positive rights obligate the landowner to perform certain actions, either for the benefit of third parties (e.g., paying rent) or the property itself (e.g., maintaining drainage systems).

A basic administrative unit (‘basic property unit’) is defined by the LADM as an administrative entity subject to registration (by law) or recording, consisting of zero or more spatial units, against which one or more unique and homogeneous RRRs are associated to the whole entity, as included in LAS.

The Spatial Unit package (depicted in blue) includes classes related to the basic spatial denominator used in LADM: the spatial unit. Spatial units are abstract spaces, designed to support the establishment and management of basic administrative units. They can be seen as geometric/topological representations of rights and administrative units (Alattas, 2022). Spatial units can be further specialised into legal spaces for building units or utility networks (ISO, 2012) and may overlap with topographic features. The Spatial Unit Package includes one sub-package, the Surveying and Representation sub-package that allows the geometric and topological representations of spatial units. LADM provides various representation options for spatial units, which are discussed in sub-section 4.1.2.

Moreover, the LADM provides code lists for various classes, offering a wide range of potential values for specific attributes. These code lists enable the adaptation of LADM terminology to local, regional, or national contexts (ISO 19152:2012). During implementation, the code list values can be customised and expanded to address local requirements while maintaining a possible linkage to the international code lists.

The main characteristics of the LADM can be summarised as follows:

- It provides a flexible concept and model that enables communication and interoperability and can be used as basis for LAS, mainly:
- The LADM forms the basis for modelling static components of LAS, referring to both spatial and non-spatial elements; hence its implementation gives the opportunity of creating relationships between spatial and non-spatial registers.
- The model is as simple as possible in order to be useful in practice and as generic as possible to serve as the data model for all types of LASs.
- It does not aim to replace existing systems, but constitutes a generic domain model, which is expandable.
- It lays the foundation for effective and progressive design and development of a LAS for those countries which currently do not have the advanced infrastructure for managing land and property information. While it supports further development and modernisation of existing LAS, enhancing both 2D and 3D LA.
- It provides a formal language (UML) for describing the information model of a LAS. Using UML is beneficial as it enables mutual harmonisation of data sets and gives the possibility of introducing a reference to the commonly used schemas from ISO standards, e.g. geometry and topology.

- It enables involved professionals, both within one country and across regions, to communicate, based on the shared vocabulary implied by the model.
- The model is object-oriented: UML class diagrams support the MDA, providing an extensible basis for the development and refinement of (2D and 3D) LAS.
- The LADM delivers a basis for extending 2D spatial representation of spatial units into the third dimension, supporting 2D, 3D and mixed representations.
- Links with other standards and initiatives:
- The model is based on the conceptual framework of “Cadastre 2014” of FIG.
- Cadastral parcels, which are included in INSPIRE Directive as the reference data constituting “a spatial frame” for other thematic data sets. They are based on LADM and they have co-developed with the editors of Edition I (European Parliament and Council, 2007). A reference to the INSPIRE Directive is included in Annex G (Informative) of ISO 19152:2012 (ISO, 2012).
- For agricultural parcels, the integration of LADM with the European Land Parcel Identification Systems (LPIS) is included in Annex H (Informative) of ISO 19152:2012 (ISO, 2012).
- Land Parcels are determined as one of the 14 global fundamental geospatial data themes by UN-GGIM (UN-GGIM, 2019). According to this data theme, land parcels are a powerful governmental tool to support to the achievement of many SDGs, including 1.4, 2.4, 8, and 11.1 (UN-GGIM, 2019). It is noted that UNGGIM Land Parcels data theme recognizes ISO 19152:2012 LADM as existing geospatial data standards on land parcels.
- Its flexible structure and concept, along with the option to extend it, provide the possibility of creating connections between LADM and other standards (e.g., national data models, INSPIRE Data Specification on Buildings, etc.).
- ISO19152 series are based on other ISO standards and reuse concepts and structures from them.

4.1.2 LADM Edition I in support of 3D functionality

The first edition of the LADM supports both 3D representations of spatial units and the seamless integration of 2D and 3D spatial units (Lemmen et al., 2010). With the growing need for 3D cadastral information, LADM has been widely adopted globally, as it facilitates the increasing use of 3D representations of spatial units without adding extra burdens to existing 2D representations (Kara et al., 2023a). LADM supports the volumetric spatial units extending above and below the earth’s surface, providing a more accurate depiction of property boundaries in complex urban environments.

The 3D capabilities of LADM have been extensively documented in various publications, ranging from visualising and querying 3D properties through a 3D platform to BIM-based applications for 3D LA and 3D property valuation (Ying et al., 2011, Karki et al., 2011, Jeong et al., 2012, Felus et al., 2014, Zulkifli et al., 2015, Dimopoulou et al., 2017, Shnaidman et al., 2019, Cemellini et al., 2020, and Kalogianni et al, 2020b).

With regards to the different spatial units supported by LADM, within the Spatial Unit package and the Spatial Representation and Survey sub-packages, the standard offers several representation alternatives ranging from simple text to 3D topology (see Figure 4.2). Spatial representation options in the current Edition of LADM are supported by corresponding spatial profiles, as described via UML diagrams, see Annex E in ISO 19152 (ISO, 2012). The choice of spatial profile within a country profile depends on its specific requirements, and it is also possible to combine multiple spatial profiles to address local needs. Depending on the implementation of the spatial profile, certain classes need to be omitted. For instance, in a 3D Topological spatial profile that describes non-overlapping 3D topological volumes, the LA_BoundaryFaceString class, which represents 2D data, should be excluded, unless there is a mix of 2D and 3D. Additionally, within the applicable constraints, the attribute “structure” in the 3D_Level class should be set to “topological”, while the attribute “dimension” in the 3D_SpatialUnit class should be set to “3D” (Kalogianni et al., 2018).

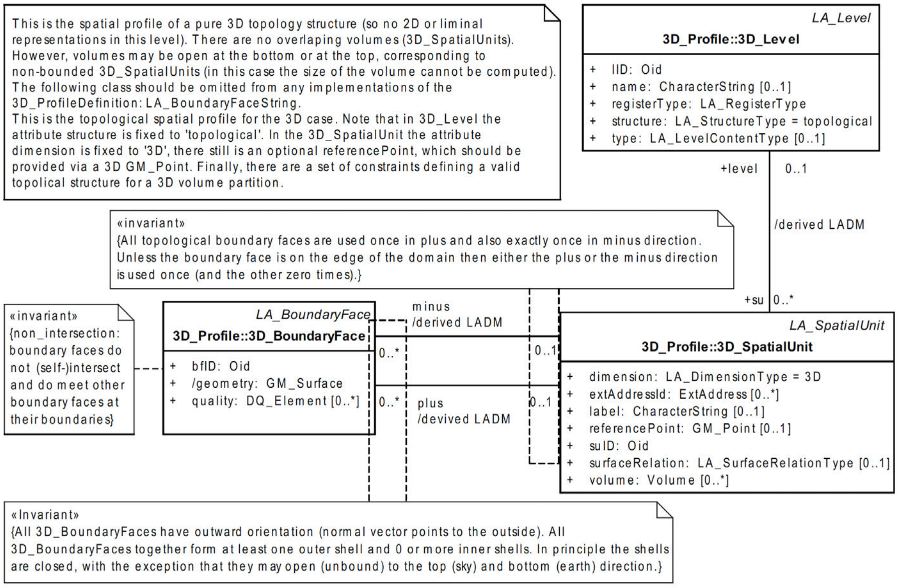

FIG. 4.2 3D Topological profile for spatial representation of LADM Edition I (Annex E, ISO, 2012)

The “3D Topological” spatial units are represented by the spatial profile detailed in Annex E in ISO 19152 (ISO, 2012) and is the only profile supporting 3D in the first edition of LADM (Figure 4.2). In the 3D topology model, volumes must not overlap but may be open at the top or bottom, corresponding to non-bounded 3D spatial units (in such cases, the volume size cannot be calculated) (Zulkifli et al., 2015). For 3D topology representation, a 3D boundary face includes positive/negative information in its association with a 3D spatial unit to indicate face orientation, but the geometric 3D volumetric primitive (GM_Solid) is not indicated, as this represents a topological view (Ying et al., 2015).

Moreover, in the Spatial Unit package of LADM, the LA_Level class defines “*a set of spatial units, with geometric and/or topologic and/or thematic coherence. This concept is important for organizing the spatial units within LADM.*” (ISO, 2012). *Levels*, support the organisation of information into groups based on thematic or geometric characteristics, allowing for more efficient management. This concept has been used for representing the needs of various countries as discussed in Zulkifli et al. (2015) and Kalogianni et al. (2017). The LA_Level class also supports the principle of legal independence, allowing different types of land registers and spatial units to be combined within one level thus integrating data from different organizations and mandates (Lemmen, 2012). The code list values for the “structure” attribute of the LA_Level class (LA_Structure_Type) include various spatial structure types (text, point, unstructured line, polygon, topology), tailored to specific land administration profile implementation.

4.1.3 The Social Tenure Domain Model (STDM)

The Social Tenure Domain Model (STDM) is a specialisation of LADM (Lemmen et al., 2015), developed in parallel to the ISO standard, with the core developers/editors of both models being the same or supportive to each other[22]. In this context, specialisation means that there are some differences between LADM and STDM, which are mostly identified in the terminology and the application area. In Edition I of LADM, the STDM is included in the informative Annex I.

Developed under the guidance of the Global Land Tool Network (GLTN) and led by UN-Habitat, the STDM aims to provide a more inclusive approach to land tenure that accommodates a wide range of tenure types, including formal, legally recognised land holdings, informal settlements, and indigenous land claims (UN-HABITAT/GLTN, 2008).

The STDM (Augustinus et al., 2006; FIG, 2010) is a land information management framework and is designed to bridge the gap between formal and informal land tenure systems.

The STDM can be defined as (UN-Habitat/ GLTN, 2023) (see Figure 4.3):

- **A concept** - as it represents all types of people-to-land relationships.
- **A conceptual model** – as a specialisation of ISO 19152:2012 and
- **An information tool** to support pro-poor LA – as it provides an open-source interface for applying the STDM concept and model.

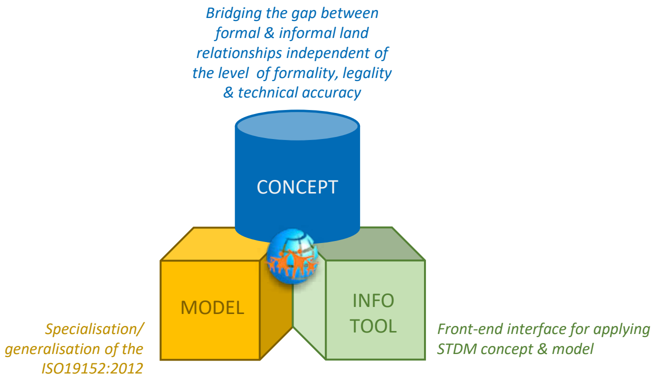

FIG. 4.3 The three notions of STDM: concept, model and information tool

22 https://stdm.gltn.net

In many countries a significant number of people-to-land relationships remain undocumented, posing a substantial barrier to economic development, particularly in rural areas (Morales et al., 2019). STDM primarily focused on the support of such situations, mainly by documenting all types of land rights, including under-documented and unrecognised land rights. However, it has evolved and today, STDM claims that It can represent all forms of land rights, social tenure relations and overlapping or competing claims to land, independently from the level of formalisation or legality of that relationship (Augustinus et al., 2006). STDM is particularly targeted to developing countries, regions with very little cadastral coverage in urban, or rural areas, post conflict zones, areas with extensive informal settlements, or large-scale customary areas (ISO, 2012).

STDM includes the collection of people to land relationships with recognition of a range of rights based on community-based participatory approaches and therefore, it contributes to more equitable and gender-responsive LAS by ensuring that women's land rights are recognised, documented and protected (Figure 4.4). STDM, in line with LADM, integrates administrative and spatial components to describe people-to-land relationships in an unconventional manner, with emphasis on social tenure relationships as embedded in the continuum of the land rights (UN-Habitat, 2008).

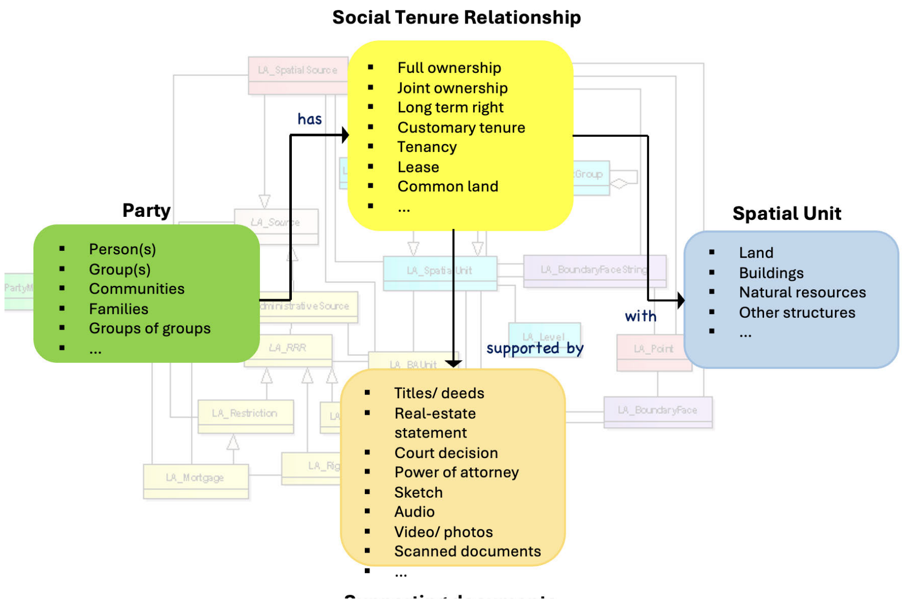

FIG. 4.4 People-to-land relationships supported by STDM (GLTN, 2017, adapted)

Furthermore, the STDM information tool provides the front-end interface for testing and applying the STDM concept and model. It is built on top of free and open-source geospatial software solutions. Specifically, the client has been developed as a QGIS Python plugin, whereas the backend is based on a PostgreSQL/PostGIS database stack.

STDM as an information tool allows for the following (UN-Habitat/ GLTN, 2013):

- development of a custom hierarchy of administrative units;
- extension of existing data management forms and design of new ones;
- management of users' permissions to specific modules is supported;
- provision of a simple report builder to generate tabular reports;
- design and sharing of custom templates of map-based documents/reports;
- generation of map-based documents in batch using default or custom templates;
- import and export of plugins that support textual and spatial data;
- a flexible tool that supports the in-practice collaboration of governmental bodies, industry and academia
- realisation as a stand-alone initiative or linked to/ embedded in national LASs.

4.2 LADM Edition II

The LADM is recognised as an international data model, due to its flexibility and wide applicability with features such as full versioning/history, integration with legal and spatial source documents, a range of 2D/3D geometry and topology options, unique identifiers, and explicit quality indicators (van Oosterom et al., 2015). Since its vote as an ISO standard, it has been extensively explored and implemented by multiple countries worldwide (Kalogianni et al., 2021). Similarly, the STDM, as presented in the previous section, has seen widespread use. ISO standards, including LADM, are subject to periodic revisions approximately every six to ten years, according to ISO regulations. This revision process starts with feedback collection from ISO/ TC 211 Member States to identify necessary updates and extensions to enhance the standard's capabilities.

During the meeting of the UN-GGIM Expert Group on Land Administration and Management that was held in 2017, in Delft, The Netherlands, it was decided that an update to the LADM was necessary, to enhance tools supporting tenure security with better coverage of LA. Specifically, UNGGIM advocated for accelerated efforts to document and recognise land rights, supporting the review of ISO 19152 by

ISO-TC211 and in close collaboration with OGC. This initiative aimed to support substantial improvement of tenure security and land rights, addressing the complex demands of LA and has been reported in ISO Stage 0 report.

Following the systematic review of ISO 19152:2012, the majority of ISO/TC 211 Participating Members supported revising the standard. In April 2018, the FIG proposed a New Work Item Proposal (NWIP) to ISO/TC 211. This proposal included extensions to the conceptual model scope, improvements to the current model, provision for encodings, process models, and improved survey model and procedures. However, this NWIP was not accepted, due to the need for LADM Edition II to be developed as a multipart standard. As a result, the ISO Stage 0 project for LADM Edition II was initiated during the 46th Plenary Meeting Week of ISO/TC 211 in May 2018 in Copenhagen, Denmark, and finalised in the 48th Plenary Meeting Week in June 2019, when the Standards Council of Canada (SCC), proposed LADM Edition II as a multi-part standard.

To lay the foundation of the LADM Edition I revision, several FIG LADM Workshops were held[23], where experts discussed improvement and extensions of the standard considering the rapid advances in technology and requirements from the users. These discussions highlighted the importance of integrating valuation and spatial planning information into the LADM, as well as enhancing 3D capabilities in both land and maritime contexts. Key aspects considered included, new information exchange mechanisms, improved alignment with other standards, refinement of Rights, Restrictions, and Responsibilities (RRRs), a more detailed survey model, enriched semantic code list values, new subclasses for spatial units, diverse representations of spatial units (in 2D, 3D or mixed dimension), updated legal profiles and the identification of legal spaces in buildings. These enhancements are crucial for advancing the LADM's functionality and applicability.

The development timeline of LADM since its initiation is illustrated in Figure 4.5.

23 One in Delft, the Netherlands, in March 2017 (FIG, 2017), one in Zagreb, Croatia in April 2018 (FIG, 2018), one in Kuala Lumpur, Malaysia in October 2019 (FIG, 2019), one online in June 2021 (FIG, 2021), one in Dubrovnik, Croatia in March/April 2022 (FIG, 2022) and one in Gävle, Sweden in October 2023 (FIG, 2023).

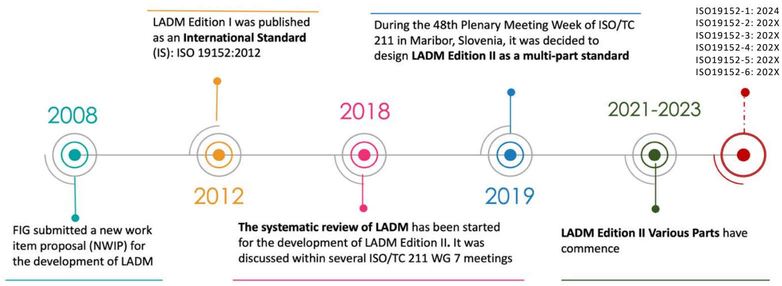

FIG. 4.5 Development timeline of LADM Editions (REF, adapted)

The multi-part approach also has an advantage for future revisions, as one part may need to be revised and the other may not (yet). Furthermore, taking into account the functions of the LA paradigm as described in section 2.1, the parts and their basic content were agreed. The scope of LADM Edition I is limited to the land tenure component of the LA paradigm (see the yellow circle in Figure 4.6), whereas LADM Edition II extends the scope of Edition I including land value, land use and land development (see the blue circle in Figure 4.6).

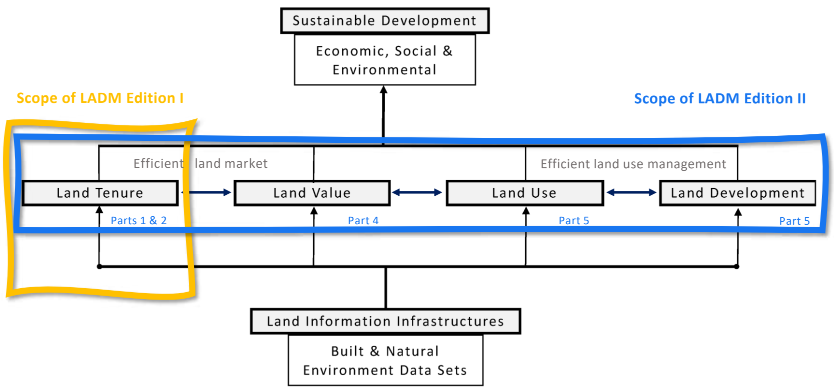

FIG. 4.6 A Global Land Administration Perspective – the LA paradigm for sustainable development and LADM Editions (Enemark, 2006; adapted)

Land, as defined in the LADM Edition II is the "*spatial extent to be covered by rights, restrictions and responsibilities and encompass the wet and dry parts of the Earth surface, including all space above and below*". Considering the comments submitted by the Standards Council of Canada (SCC), a new term with a wider meaning is introduced in LADM Edition II, 'georegulation'. It is defined as "*the activity to delimit and assert control over geographical spaces through regulations*" (ISO, 2024). Georegulation allows for the creation of various geographic spaces serving multiple functions within the contexts of international law, constitutional law, administrative law, private law and customary law (ISO, 2024). According to ISO 19152-1:2024, those spaces can be used, for purposes such as delegating regional powers, controlling territorial accessibilityfor security or health reasons, organising the circulation of people, goods and information, managing resources or conserving areas. These geographic spaces can be juxtaposed or overlap, creating a complex legal spatial representation of reality.

LA is a multifaceted discipline with diverse functions, as described by Enemark (2006), where 3D representations are becoming increasingly emerging. This comprehensive approach ensures that LADM remains relevant and robust, adapting to the evolving needs of modern LA. Based on the afore mentioned, the following structure for LADM Edition II has been agreed upon (Figure 4.7):

1. Part 1 – Generic conceptual model
2. Part 2 – Land registration
3. Part 3 – Marine space georegulation
4. Part 4 – Valuation information
5. Part 5 – Spatial plan information
6. Part 6 – Implementation aspects

The inclusion of the marine georegulation, land value information, as well as spatial plan information in LADM Edition II, aligns well with its scope and the definition of land (Figure 4.6). The multi-part approach ensures that each Part acts as an independent standard, undergoing its own standardisation process. It should be noted Edition II to be backwards compatible with Edition I, with each part functioning as a standalone standard.

This methodical separation allows for detailed attention to specific aspects of LA, enabling targeted development and refinement of each part. Consequently, a NWIP has been formulated for each part, from Part 1 to Part 5.

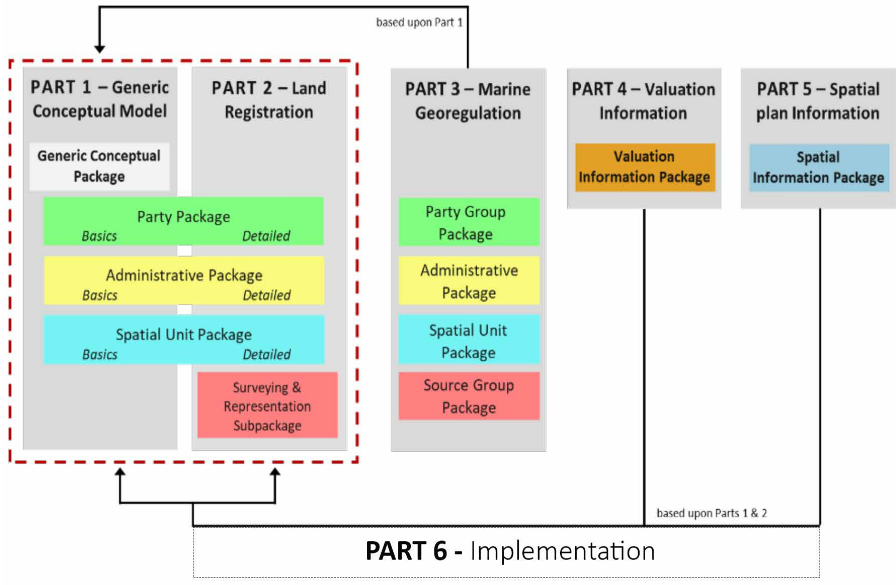

FIG. 4.7 Parts and Packages Design of LADM Edition II

The development of LADM Edition II is strategically aimed at fostering standardised information services, both nationally and internationally, facilitating the seamless sharing of LA domain semantics across organisations, regions, and countries. This standardisation is crucial for enabling the necessary translations and interpretations needed for effective and efficient LA practices. The primary considerations that are guiding the design of LADM Edition II aim to ensure that the standards are practical, comprehensive, and adhere to internationally recognised frameworks. These considerations include:

1 The standard covering common aspects shared by spatial units created by LA/georegulation. This involves defining a broad range of components such as property rights, restrictions, responsibilities, and spatial units, which are common to different systems of LA across various jurisdictions.

2 The standards are grounded in the conceptual framework of “Cadastre 2014” of the FIG. Therefore, the principle of legal independence can be realised either through completely separate LADM implementations for each layer or by implementing only the spatial unit package of LADM per layer. This flexibility allows for adaptations to local or regional requirements while maintaining coherence with the broader context.

3 The design of the standard to be as simple and practical as possible to ensure it is user-friendly. By minimizing complexity in the conceptual model design, the standard aims to be readily applicable and easily adoptable by professionals and organisations, reducing the need for extensive training or specialised knowledge.

4 The alignment with the geospatial components of the LADM with the ISO/TC 211 conceptual model, i.e. basic types as defined in ISO 19103, geometric elements as defined in ISO 19107 and the general feature model as defined in ISO 19109, which sets out rules for creating schemas for feature types and their relationships.

Regarding the impact of LADM Edition II on SDGs and its alignment with relevant ISO standards, and according to the assessment of ISO/TC 211 (Kara et al., 2023a), LADM Edition II may contribute to the following SDGs: 1 – No poverty, 2 - Zero Hunger, 5 - Gender Equality, 9 - Industry, Innovation and Infrastructure, 11 - Sustainable Cities and Communities, 14 - Life below water,15 - Life on Land and 8 - Decent Work and Economic Growth. Additionally, as per ISO19152-1: 2024, the geospatial aspects of LADM Edition II will adhere the ISO/TC 211 conceptual model, i.e. basic types are defined in ISO 19103, geometric elements are defined in ISO 19107 and the general feature model used in this document is defined in ISO 19109.

The rest of this section provides an overview of the process followed within ISOTC211 for the revision of the LADM and the requirements that guided the design of the survey model of Part 2. Following the various Parts of LADM Edition II are introduced in sub-section 4.2.2.

4.2.1 Requirements' specification during the revision process

Within ISO the formal incorporation of requirements into standards is a relatively recent development. Initially, the first edition of the LADM did not include requirements. However, in the PhD thesis of Lemmen (2012), which laid the groundwork for LADM Edition I, user requirements were already introduced. They had a reference to Land Administration Guidelines issued by UNECE (1996) and addressed general requirements for standardisation, though, they were not integrated into the standard itself.

This thesis served as a foundational reference for incorporating requirements into subsequent editions of the LADM and specifically, for Parts 1 and 2 of the LADM Edition II. For the formulation of the requirements in Parts 3, 4, and 5 consulting with domain-specific experts was essential, ensuring that each standard accurately reflects the needs and technical nuances of different areas within LA. As a result, precise and applicable requirements were formulated for each part, namely:

- **Part 3:** Experts in hydrography were involved, primarily through collaboration with the International Hydrographic Organisation (IHO).
- **Part 4:** For valuation-related aspects, expertise was sourced from FIG Commission 9 “Valuation and the Management of Real Estate” and the Royal Institution of Chartered Surveyors (RICS).
- **Part 5:** Spatial planning experts, particularly from FIG Commission 8 “Spatial Planning and Development”, were consulted to shape the requirements of Part 5, that support urban and regional planning processes within the context of LA.
- **Part 6:** close collaboration between ISO and OGC through the LA Charter for a Standards Working Group that has been formed in the middle of 2024.

The ISO development process consists of several steps as presented in Figure 4.8 and at each stage the proposal is reviewed and evaluated by domain experts within ISO/TC211.

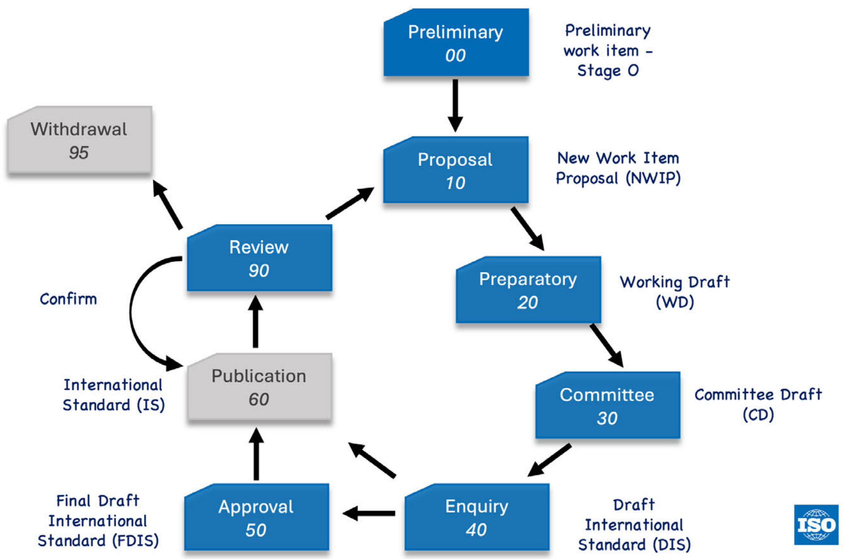

FIG. 4.8 ISO revision process and steps towards standardisation of LADM

During the early stages of standardising LADM Edition II, requirements were not yet included in the Working Drafts (WD) and were only formally introduced in late 2022 with the Committee Draft (CD) and Draft International Standard (DIS) stages for Parts 1 to 5. In 2023, balloting and feedback from participating countries were reviewed and refined, leading to a comprehensive set of requirements aligned with the needs of the international LA community. These requirements, that guided the design of the various packages within LADM Edition II, as detailed in Kara et al. (2023a), are clearly defined and organised by LADM parts. The foundational requirements in Part 1 also apply to Parts 2 through 5, ensuring consistency and interconnectedness across the standard. The timeline of the standardisation of LADM parts is presented in Figure 4.9.

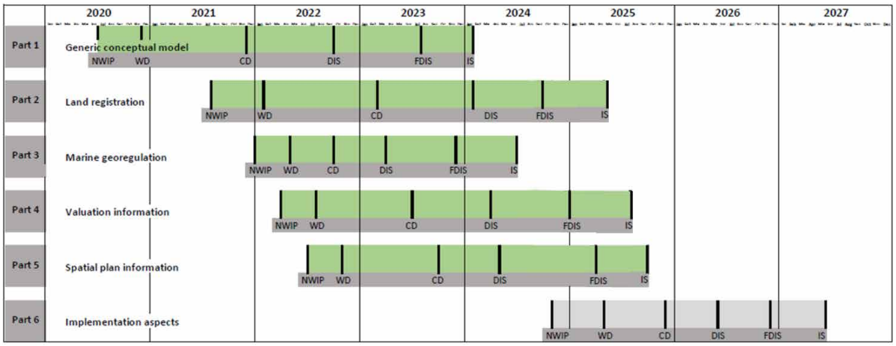

FIG. 4.9 Standardisation process of LADM Edition II parts

As illustrated in Figure 4.9, Part 1 was approved and published as an ISO International Standard (IS) in early 2024. This was followed by the vote of Part 3 as an IS in mid-2024, while Part 2 reached the publication stage as ISO in the second quarter of 2025. Furthermore, Parts 4 and 5 were very recently published as IS, in mid-2025.

In the context of this dissertation, which directly contributes to Part 2, specific requirements supporting the refined survey model have been developed to enhance the standard's functionality. These requirements, listed in the table below, are aligned with the final numbering presented in Kara et al. (2023a) and incorporated into the ISO draft stages. Consequently, the non-continuous numbering in the table reflects this alignment with the standardised framework and the progression of the ISO draft development process.

TABLE 4.1 The survey-related requirements for LADM edition II - Part 2 (Kara et al., 2024a)

Requirement	Requirement name / Solution	Description
All requirements in Part 1 apply to Part 2.	Requirement 2-1 'Based on General Conceptual Model'	This part of the standard is based on Part 1 – General Conceptual Model. All requirements contained in 19152-1 shall apply to this part of the standard.
Distributed environment	Requirement 2-4 'Different Organisations'	Land administration data can be maintained by different organisations. And within one organisation at many sites. Administrative territories for organisations can be completely different. The LADM based systems shall be implemented as a distributed set of (geo-) information systems, each supporting the maintenance processes (transactions in land rights, establishment of rights, restrictions and responsibilities) and the information supply of parts of the data set, represented in this model.
No duplications unless something has different meanings in different models (roles)	Requirement 2-5 'Keep Data to Source'	Land administration data shall be kept to the source within Spatial Data Infrastructure (SDI). Today all data (spatial and thematic) can be stored in a Data Base Management System (DBMS). Information products are becoming flexible combinations of digital data components and additional facilities and services. This can replace the exchange of copies of data sets between organisations. Multi source information products require avoidance of redundancy and good standardisation protocols.
Continuous source updates maintenance	Requirement 2-6 'Authentic Source Documents'	Inclusion of new data and data updates shall be documented. This concerns legal administrative data, spatial data and/or technical data.
Transparency in history management and updates	Requirement 2-7 'Transparency'	All updates shall be traceable in LADM compliant LASs
Responsible person should be part of source data	Requirement 2-8 'Responsible Person'	The names of persons responsible for transactions shall be part of the source data set (conveyors, surveyors, registrars, etc.). This is one reason for management of history and for documentation of all updates.
All spatial units should be specified in a seamless way	Requirement 2-12 'Continuum of Spatial Units'	Representation of a broad range of spatial units, with a clear quality indication, shall be supported by an LADM compliant LAS. Spatial units are the areas of land (or water – e.g., water rights and the marine environment) where the rights and social tenure relationships apply. Spatial units can be represented as a text ("from this tree to that river"), as a sketch, as a single point, as a set of unstructured lines, as a surface, or as a 3D volume.

>>>

TABLE 4.1 The survey-related requirements for LADM edition II - Part 2 (Kara et al., 2024a)

Requirement	Requirement name / Solution	Description
All spatial units should have a unique identifier	Requirement 2-13 'Spatial Unit Identifiers'	Spatial units shall have a unique identifier. A key component in LASs is the spatial unit identifier, the parcel identifier or the unique parcel reference number. This acts as a link between the parcel itself and all record related to it. It facilitates data input and data exchange. There can be a need to change identifiers during data collection.
Cadastral maps should be based on surveys	Requirement 2-14 'Spatial Source Based Maps'	Cadastral maps shall be based on spatial sources, such as surveys, design sources, topographic maps, etc.
Different data acquisition methods can be used to identify boundaries of spatial unit	Requirement 2-15 'Data Acquisition Methods'	Surveying of boundaries shall be supported. Surveys may concern the identification of boundaries of spatial units on a photograph, an image, or a topographic map. Surveys can be conventional land surveys, based on hand-held GPS. In all cases the representation of 'legal' reality is differentiated from the 'physical' reality. There may be sketch maps drawn up locally. Depending on the local situation, different registrations or recordings of land rights are possible.
Cadastral surveys should be represented in a reference system	Requirement 2-16 'Cadastral Reference System'	Efficient LASs compliant with this part of LADM shall be capable of producing co-ordinates, forming an essential component of cadastral systems. Provisions may be made to accommodate future changes in the reference system that may occur as a result of technical improvements. These may affect all co-ordinate-based systems. Imagery can be used depending on the user requirements, cost, and timing among other factors. It can be possible to include all documentation on data collected as evidence from the field.
Quality of cadastral data should be specified	Requirement 2-17 'Data Quality'	The cadastral information shall be as complete as possible, reliable (which means ready when required), and rapidly accessible. Users of cadastral information need clarity, simplicity and speed in the registration process. Consistency between spatial and legal administrative data is important. Topology integrated with geometry and other attributes is relevant. The system must be ready to keep the information up to date. Data quality of spatial data may be improved in a later stage of development of a LAS, this has to be documented. For combined data products from different sources the quality descriptions and meta data related to the original data are relevant in relation to liability and information assurance.

This evolution in ISO's approach to standard development, particularly within the LA domain, underscores a transition towards a more structured and requirements-driven methodology. This shift aims to ensure that the standards developed are not only robust and comprehensive but also finely tuned to meet the specific needs of users while adhering to global best practices.

The adoption of a requirements-based approach to standardisation offers multiple benefits:

- **Explicit stakeholder input:** Stakeholders within the domain can explicitly express their needs and expectations. This direct input ensures that the resulting standards reflect real-world requirements and challenges, making them more relevant and applicable.
- **Clear and concise introductions:** For those not familiar with LA and LADM, standards that begin with a clearly defined set of requirements provide a concise and accessible introduction. This helps readers/ users to quickly understand the core concepts and objectives of the standard, facilitating easier application and adaptation.
- **Solid foundation for developers:** Models' developers benefit from a well-defined set of requirements which serve as a solid foundation for their developments and justify their design choices. This structured approach reduces ambiguity, enhances the logical flow of the development process, and supports the creation of more effective and efficient standards' implementation.
- **Implementation verification:** the inclusion of an Abstract Test Suite in Annex A of the various parts provides a valuable tool for verifying compliance. This suite is based on the requirements and allows users to systematically check whether their implementations are in line with the specific part, package, or class, ensuring that their development is compliant with the standards (also by providing the level of compliance).

A diverse range of experts from academia, industry, national standardisation bodies and professional organisations are engaged in the revision process. This includes key organisations such as ISO, FIG, OGC, UN-Habitat, UN-GGIM, the Global Land Tool Network (GLTN), IHO and RICS. The cooperation between OGC and ISO is expected to contribute to enhance the effective implementation and development of the standards. A White Paper on Land Administration prepared by the OGC's Domain Working Group Land Administration (OGC, 2019) serves as a starting point for the collaboration, highlighting the need of the LADM operationalisation.

4.2.2 LADM Edition II Parts

The publication of LADM Edition II as a multi-part series has resulted in the development of six standards, expanding its scope beyond Edition I. While Parts 1 and 2 maintain backward compatibility with the first Edition, the new Edition encompasses additional aspects such as value and use, whereas Edition I focused solely on tenure, which is now addressed in Parts 1 and 2 (Figure 4.6).

Figure 4.10 shows the class diagram for LADM Edition II parts 1, 2, 4 and 5 and their (inter) relationships. For clarity, certain elements such as VersionedObject class and its relationships and some relationships of LA_Source and its subclasses, are omitted from the diagram.

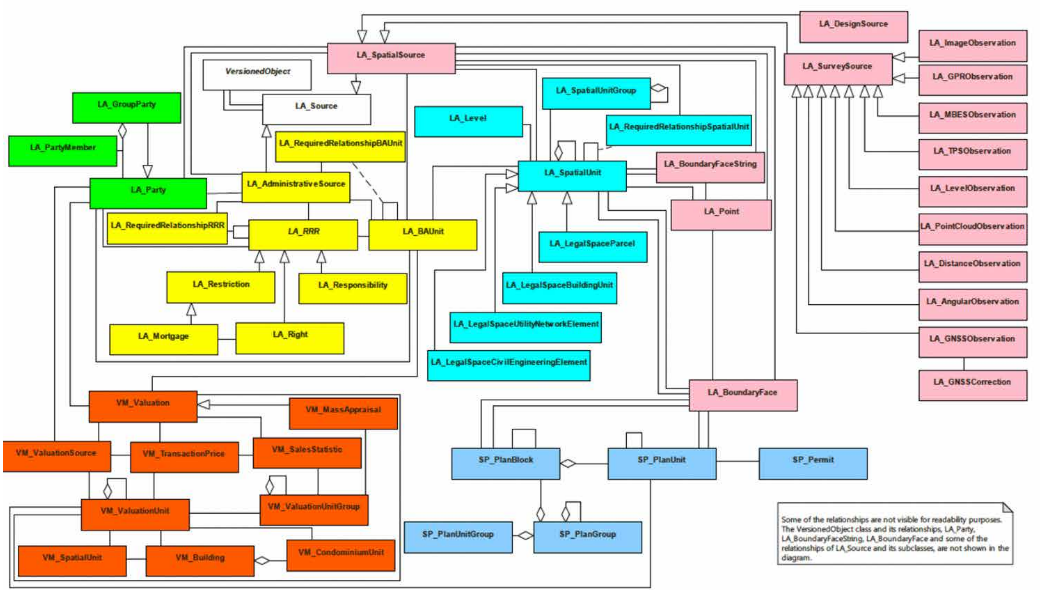

FIG. 4.10 Parts 1, 2, 4 and 5 of LADM Edition II and their relationships (Kara et al., 2024a)

Parts 1, 2, 4 and 5 are structured around the principles of “Cadastre 2014” (Kaufmann and Steudler, 1998), while their geospatial specifications adhere to the ISO/TC 211 conceptual model. This alignment facilitates spatial data handling across LAS in a consistent way based on international geospatial standards, ensuring interoperability through all the LA aspects supported by the various parts of LADM Edition II. Additionally, all LADM parts addressing LA and georegulation (ISO 19152 series, from Part 1 to Part 5) make use of the generic “General feature model” as described in ISO 19109 (Kara et al, 2023c). It presents a feature-oriented approach where a feature may have thematic, temporal, spatial, quality, etc. attributes, while the spatial geometries is derived directly from this structure.

I ISO 19152- 1:2024: Generic conceptual model

Part 1 serves as a foundational, high-level, umbrella standard that underpins and supports other more specific LA/ georegulation models expressed in the subsequent parts of the LADM Edition II (Parts 2, 3, 4 and 5). It encompasses fundamental concepts and defines the basic components and relationships that are common across all spatial units created by LA /georegulation, while it supports implementation in a distributed organisational environment.

It is noted that Part 1 will not only be backward compatible with the previous Edition of the LADM, but also with the IHO S-121 Maritime Limits and Boundaries standard (IHO, 2016), which is being used as one of the foundations for the development of Part 3 of LADM Edition II. The generic conceptual model of the LADM is based on six basic classes. LA_Party, LA_RRR, LA_BAUNIT and LA_SpatialUnit are inheriting from VersionedObject and are associated to LA_Source (Figure 4.11). VersionedObject class is included, in Edition II with standardised support for the bi-temporal model with intervals for both system and real-world times (Thompson and van Oosterom, 2021).

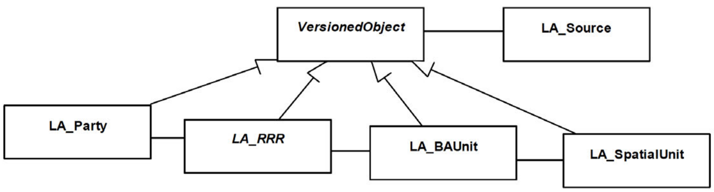

FIG. 4.11 Basic classes of the core LADM (ISO, 2024)

For the common packages (as presented in Figure 4.7), in Part 1 the terms defined in these packages are only introduced, while more detailed description of these packages is included in Part 2. Therefore, it doesn’t contain information about the attributes of any classes, except for the “Generic conceptual model” (namely: VersionedObject, LA_ Source, and the datatypes Oid and Fraction), while not all the classes of the packages are included as they do not apply to all parts (i.e. the Surveying and representation sub-package is not included, since it is not applicable for Marine georegulation).

II ISO 19152- 2: Land Registration

The LADM Edition I concentrated on land registration, which is now addressed in Part 2 of the LADM Edition II, with several refinements aiming to add more semantics to the LADM.

The continuum of land rights (Figure 2.2) (UN-HABITAT, 2008) is also followed in the design of this part. In addition to the classes introduced in Part 1, Part 2 contains the LA_Mortgage subclass of LA_Restriction, which is associated to the LA_Right class. Moreover, the different types of spatial units related to LA/ georegulation with associated spatial and thematic attributes, are refined into four specialisations (Figure 4.12) within the Spatial Unit package:

- the traditional parcel;
- the utility networks, concerning their legal spaces;
- the building units, concerning their legal spaces and
- the infrastructure objects, concerning their legal spaces.

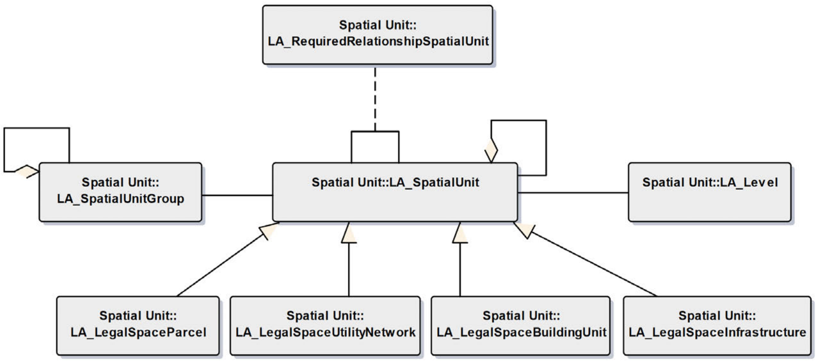

FIG. 4.12 The four subclasses of LA_SpatialUnit in the Spatial Unit package in Part 2 - Land Registration (Kara et al., 2024a)

The refinements of Part 2 are listed below, while those related with this research are briefly analysed in the following paragraphs. This concerns:

- the LADM refined survey model;
- a set of supported representations of spatial units in 2D, 3D or mixed dimensions – Spatial Profiles;
- standardised support for the bi-temporal model with intervals for both system and real-world times;

- semantically enriched and versioned code lists;
- refined legal profiles;
- changes and updates in the Annexes.

One of the core contributions of this dissertation, the refinement and enrichment of the LA_SpatialSource class to support SDL, as analysed in section 6.3. This analysis reflects the ongoing efforts to enhance LADM's capability in managing spatial sources effectively, by refining the survey model which is detailed in ISO 19152-2. Recognizing the importance of 3D data representation, Part 2 includes refined 3D spatial profiles detailed in Annex C (ISO, 2025a). These profiles that support the entire lifecycle of 3D spatial units, are based on research by Thompson et al. (2015; 2016), Kalogianni et al. (2020b) and FIG (2018b) and are discussed in section 6.1.

The class VersionedObject is introduced in the LADM to manage and maintain historical data in the database. This class ensures that all data entries and revisions are timestamped, allowing the database content to be reconstructed to any historical state and enabling the tracking of all events. In Part 2 the VersionedObject class has fourteen subclasses, with nine additional classes that inherit from VersionedObject, as depicted in Figure 4.13.

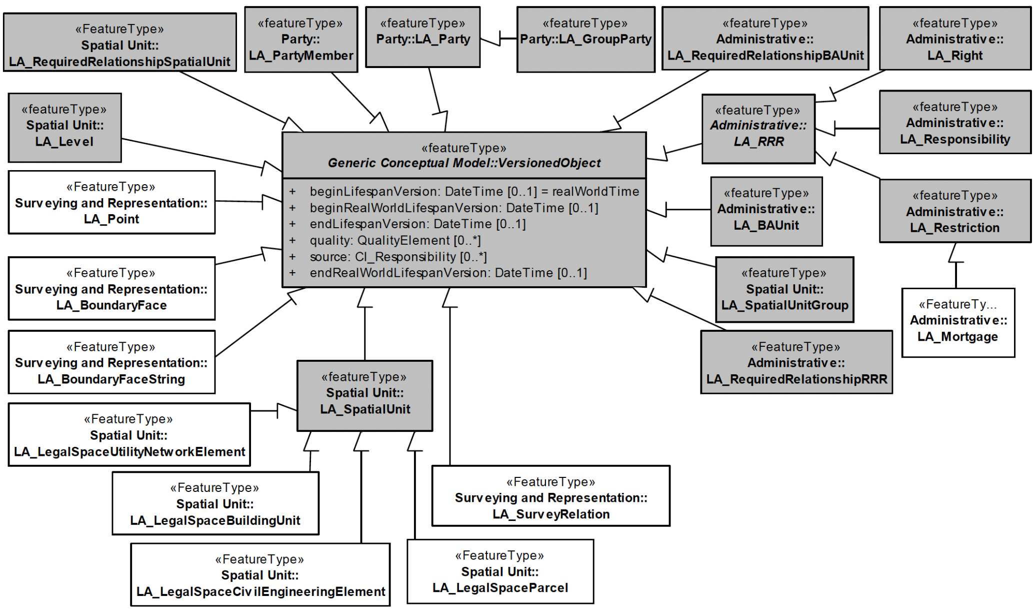

FIG. 4.13 Class VersionedObject with subclasses (ISO, 2025)

The update and restructuring of the Annexes of Part 2 of LADM Edition II includes three main topics: the STDM as a normative Annex, a metamodel for code lists and the integration of LADM and OGC IndoorGML, as analysed below:

- After a number of years of piloting, STDM has reached a level of robustness and in the second edition of LADM, which includes twelve Annexes, the designation of the STDM from an informative annex in Edition I to a normative Annex in Edition II is included, signifying its elevated importance. In this context, and as in Edition II, it is proposed that legal spaces of spatial units can be linked to physical objects– by identifiers or re-use of descriptions of space. An IndoorGML-LADM model is included in Annex K of the draft standard as an example. Based on Alattas et al. (2017) and Alattas (2022), the integration of IndoorGML and LADM is proposed to define access rights of indoor spaces based on ownership and/or the functional right of use.

- Furthermore, to be able to provide semantically enriched, structured and versioned code lists in Part 2, a metamodel is introduced in Annex G. This metamodel is based on the collective research by Paasch et al. (2015), Stubkjær et al. (2018), Stubkjær and Çağdas (2021) and Kara et al. (2022), which addresses the need for international standards while accommodating local jurisdictional specifics. This approach ensures that LADM remains flexible and applicable across different legal and cultural contexts, enhancing its global applicability and effectiveness.

- An IndoorGML-LADM model is included in Annex K as an example of linking physical and legal objects. The combined use of OGC IndoorGML and LADM is proposed to be used in order to define and represent the accessibility of the indoor spaces based on the ownership and/or the functional right of use (Alattas et al., 2017; Alattas, 2022).

- Representation of legal spaces in buildings based on LADM (Annex L).

III ISO 19152- 3: Marine georegulation

The oceans are of great importance to humanity, with specific coastal areas falling under the jurisdiction of nation-states. Coastal states have authority over designated maritime zones, where users and states hold RRRs. Beyond these zones, no state exercises sovereignty, and rights to resources are vested in humanity (ISO, 2024b; UN, 1982). In certain cases, private rights exist, usually related to activities, such as those associated with fishing or resource extraction. Individuals may also hold property rights on land adjacent to water, potentially extending into the water-covered area. For instance, in coastal areas, landowners adjacent to a lake or river may hold riparian rights, granting them the ability to extract water for irrigation, access the shoreline, etc. These rights often coexist with public rights, such as navigation or fishing.

Therefore, the third part of ISO 19152 provides the concepts and structure for standardisation for georegulation in the marine space. Specifically, ISO 19152-3 (ISO, 2024b) introduces the broader term "georegulation", in the marine environment, defined as the activity of delimiting and asserting control over geographical spaces through regulations.

Part 3 addresses the information related to management of legal spaces, such as the international maritime limits and boundaries, marine living and non-living resources management areas, marine conservation areas, etc. and their related rights and obligations. This part of 19152 ISO-series establishes the common elements and basic schema to structure marine georegulation information system, harmonising the description of RRRs and aligning land concepts with marine aspects from the marine domain based on IHO S-121 Maritime Limits and Boundaries Product Specification (Lemmen et al., 2023).

The application schema model for managing RRRs for georegulation in marine spaces, developed within the context of LADM and aligned with the S-100 Universal Hydrographic Model and the IHO S-121 standard on Maritime Limits and Boundaries (IHO, 2019), is illustrated in Figure 4.14. The schema is organised into four group sections—Party, Administrative, Source, and Feature/Attribute Spatial Unit—reflecting the packages inherited from ISO 19152-1:2024 and integrates the feature structure established in ISO 19109 (ISO, 2015) and ISO 19110, which implement the spatial unit concept defined in ISO 19152-1. Additionally, the schema introduces the MG_Governance class within the administrative group to enhance its capabilities.

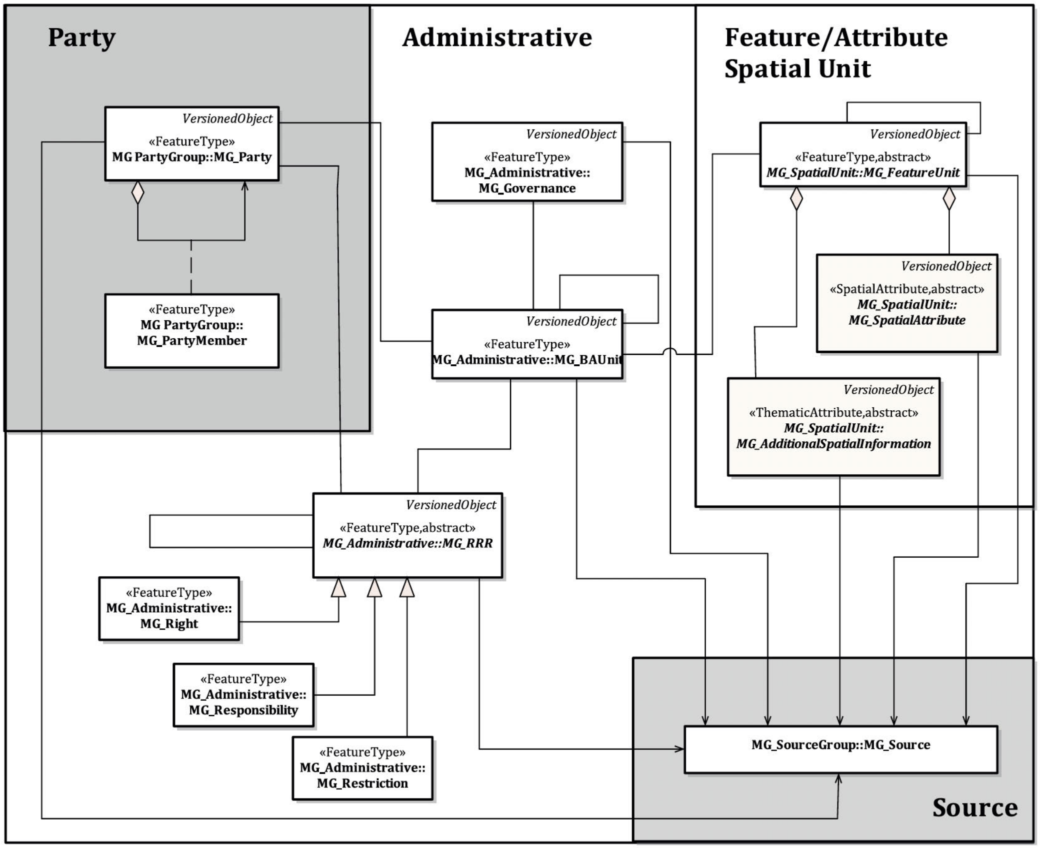

FIG. 4.14 Marine georegulation application schema model of ISO19152-3 (ISO, 2024b)

Although georegulation in marine environments may differ from LA, the fundamental structure of RRRs established in ISO 19152-1:2024 remains applicable. Marine activities, such as transportation, resource extraction, and food production (including fishing and marine aquaculture), are highly significant. Different rights and obligations can apply to marine zones, including the surface, the water column, and to the seabed. The model defined in Part 3 can be applied to marine cadastres, and other use cases, such as conservation areas, living resources and fishery management areas, non-living resources management areas, seabed tenure, and more. It can also support data management in accordance with the United Nations Convention on the Law of the Sea (UNCLOS) (UN, 1982) and other conventions, such as administrative areas defined for safe navigation defined under the International Convention for the Safety of Life at Sea (SOLAS) (UN, 1980).

IV ISO 19152- 4: Valuation information

In the first edition of LADM (ISO, 2012), there was only one external class 'ExtValuation', limited to basic attributes such as value, value type, and value date, which, while useful, did not comprehensively address all the aspects needed for a detailed property valuation (Kara et al., 2023b). This limitation was acknowledged as valuation was outside the scope of the first edition of the standard.

For accurate valuations, the valuation system must also include data on the instance property type, size and building year, as well as the quality of the property and maintenance condition (Kara et al., 2023b). To support this, the second edition of LADM, introduces a package dedicated to valuation information. Part 4, the Valuation Information package (LADM_VM), focuses on valuation information within the context of LA aiming to define the characteristics and semantics of valuation information maintained by public authorities. This package was initially proposed by Çağdaş et al. (2016) and has undergone several revisions to refine its effectiveness and applicability, as detailed in subsequent work by Kara et al. (2023a).

LADM_VM (Figure 4.15) is structured to support all stages of administrative property valuation, which includes identification of valuation units, both single and mass appraisal methods for valuation, transaction prices' recording, sales statistics representation and appeals handling (Çağdaş¸ et al., 2016; Kara et al., 2018a; 2020; 2021).

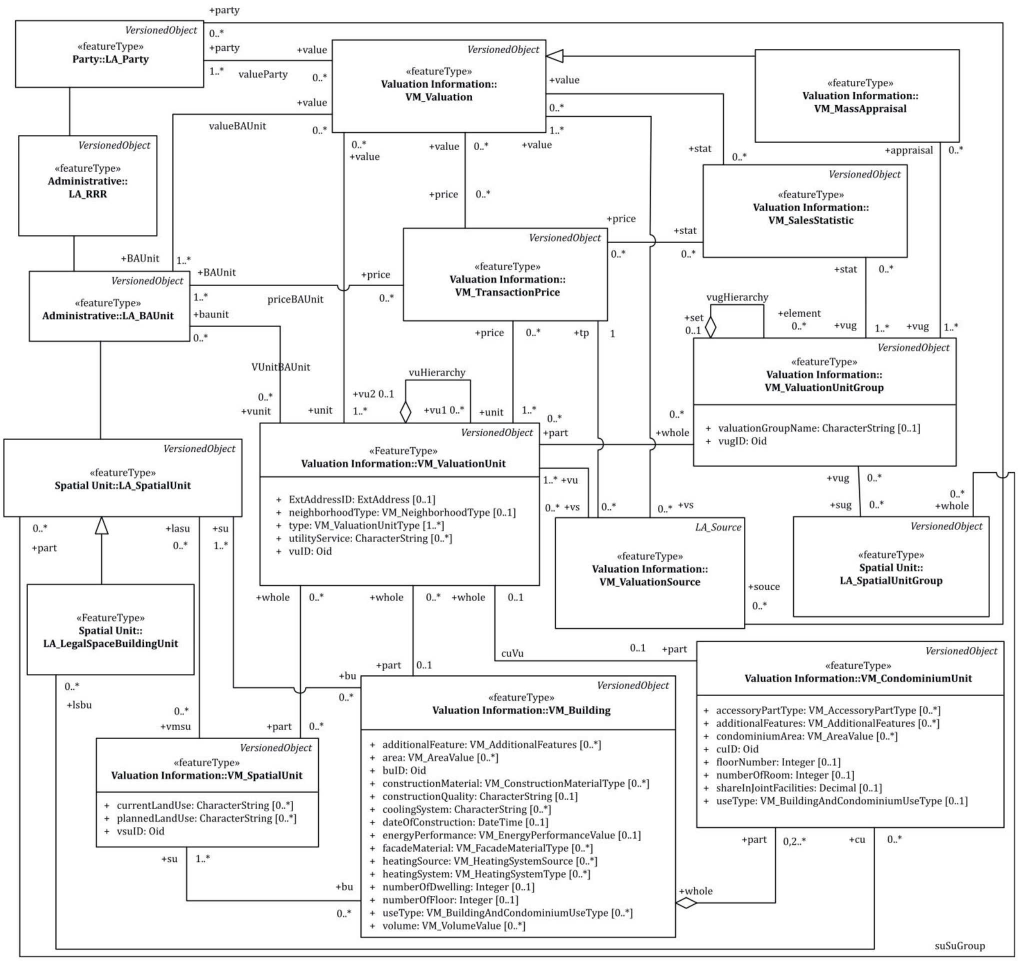

FIG. 4.15 Overview of the LADM Valuation Information Package and its relations with core LADM classes (Kara et al., 2024a)

The importance of 3D factors on property valuation, such as the height of the property location, as well as the environmental influences (i.e. noise, safety and routing) are recognised and are supported by the Valuation Information Package (VM) of LADM. It is therefore expected that LADM Valuation implementation will use the 3D possibilities of the LADM core (Kara et al., 2018a; 2020; 2021). A country profile developed using LADM_VM can be used as a basis for the dissemination of valuation information associated with 3D valuation units (e.g., condominiums) and groups (aggregation of valuation units, e.g., building floor in multi-occupied building, multi-occupied building, street, district, valuation zone and so forth). Publishing the statistical data associated with the 3D units can enable more effective communication with users (Kara et al., 2023).

V ISO 19152- 5: Spatial plan information

Part 5 of the LADM Edition II focuses on spatial planning and development and is based on a thoughtful integration of established frameworks and projects. This part incorporates insights and methodologies from the Plan4all project (Cerba, 2010) and the Land Use data theme of the INSPIRE Directive (INSPIRE, 2012), enhancing the depth and applicability of the standards for spatial planning.

Plan4all is a conceptual framework which was initiated by the European Union in 2009 to achieve interoperability of spatial planning information (Murgante et al., 2011). The project aims to improve the interoperability of spatial planning data by providing a comprehensive approach to handle geospatial planning data that is crucial for effective urban and regional planning (Cerba, 2010), while ensuring compatibility with INSPIRE. Plan4All's model differentiates between existing and planned land use. On the other hand, the INSPIRE directive sets out a framework for making geographic information available across Europe to support environmental policies and activities (INSPIRE, 2012). The Land Use data theme of INSPIRE focuses on the classification and use of land for various planning and policy-making processes.

The LADM Part 5 – Spatial Plan Information (ISO 19152-5:2025) aims to integrate land registry and planned land use information within a unified conceptual model facilitating the shared use of both datasets (ISO, 2025b). It supports the planning hierarchy, organises plan units into plan blocks, and provides extensible code list values for the spatial (sub) functions of plans. Additionally, it enables permit registration related to the relevant plan unit and allows for open dissemination and clear 2D and 3D visualisation of planning information.

The Spatial Plan Information Package (LADM_SP) (initially developed by Indrajit, et al. (2020; 2021) supports the conversion of planned land use (zoning) into RRRs, while there is also support to accommodating hierarchy in spatial planning. The main classes of this package are illustrated in Figure 4.16.

LADM_SP reuses the core LADM classes from Party and Administrative Package (as described in ISO 19152-1: 2024 and ISO 19152-2: 202X) to represent spatial planning processes. The package models parties involved in providing legal aspects (arising from the RRRs) from spatial planning processes using the class LA Party. The spatial representation (geometry and topology) of the LADM_SP classes is provided by associating to the LA classes LA_BoundaryFace and LA_BoundaryFaceString. Finally, Part 5 is expected to contribute to the need for a clear way to store the urban rules and make them available for processing.

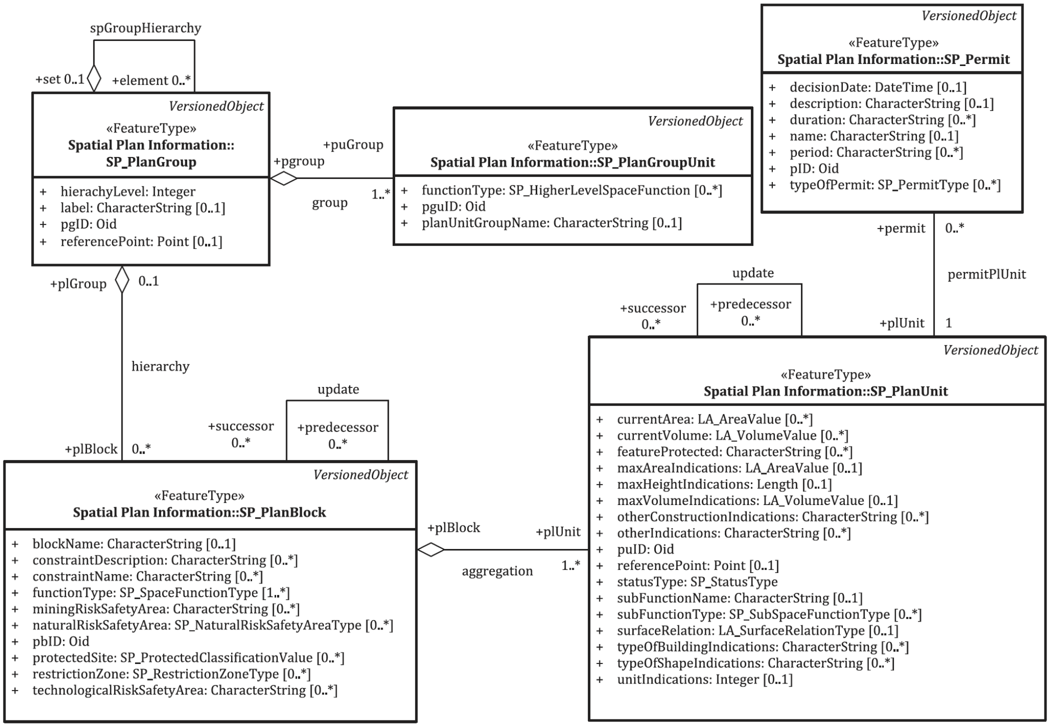

FIG. 4.16 Content of LADM spatial plan information package (ISO, 2025)

VI ISO 19152- 6: Implementation

Part 6 of LADM Edition II, initiated in middle 2024, focuses on various aspects of implementing the standard. In June 2024, the OGC established an LADM Standards Working Group (SWG) to integrate the LA needs of its members into the development of the encoding standard. The SWG will assess the necessity for formal profiles, extensions, or best practices to address these needs (OGC, 2024). This collaborative approach ensures the effective implementation of the LADM conceptual model, leveraging insights from the OGC community and maintaining flexibility to support diverse use cases.

The growing interest in LADM, as evidenced by various country profiles and technical implementations (Kalogianni et al., 2021), underscores the need for a standardised encoding framework to support its implementation. Currently, countries implementing LADM either develop or procure technical encodings, independently, as the first edition of LADM is merely a conceptual model (Kalogianni et al., 2021a; OGC, 2024a). This approach has resulted in a multitude of different solutions, reducing interoperability and increasing implementation costs. A standardised encoding would facilitate greater consistency, enabling vendors to reuse their LADM software across multiple countries and jurisdictions, thereby reducing costs and improving compatibility.

The LADM SWG will not develop further conceptual model parts of the LADM, as its main deliverable is to develop an encoding standard of the five Parts of the ISO 19152 series. The content of the encoding standard will derive requirements from the conceptual models of the respective LADM Parts.

Therefore, the initial scope of the LADM SWG, which will cover the LADM Part 6 context is the following (OGC, 2024a):

- Methodology to develop LADM country profiles (will be Part 6a of ISO19152-6)
- Technical model / encoding according to one or more formats. One or more encoding formats will be considered, referencing international standards such as Geography Markup Language (GML), JSON, GeoJSON, Features and Geometries JSON (JSON-FG), and others. In this scene, the OGC API family of standards-compliant recommendations for the development of interoperable LADM schema-based information systems will be investigated.
- Management/maintenance rules for semantically rich code list values (based on Simple Knowledge Organisation Systems (SKOS)) – a metamodel.
- Workflows/procedures of the most important LA processes. The standardisation and implementation of such processes with relevant digital technologies are expected to be investigated, while, among others, the relationships between the LADM and the instruction guidelines for property measurement, such as the International Property Measurement Standards (IPMS) and the International Land Measurement Standard (ILMS), is planned to be included in the processes section of Part 6.
- In case that adjustments to the LADM Parts 1-5 are realised through ongoing ISO processes that require new conceptual models, the SWG will consider undertaking conceptual model development at that time.

4.3 Advancements in country profiles and software solutions for LADM

worldwide, regardless of the registration system that applies to a jurisdiction (see FIG 2017, 2018a, 2019, 2021, 2022; Kalogianni et al., 2021a and Lemmen et al., 2020). STDM is mainly implemented in developing countries with support of UN-Habitat/ GLTN, while the geospatial software and consulting industry is increasingly interested in providing LADM-based solutions. LADM's flexible concept and structure allows for extensions and adaptations to suit local contexts. Additionally, the conceptual model supports external links to other databases, facilitating the development of comprehensive information infrastructure systems.

This section provides an overview of LADM implementations since its adoption as an IS in 2012. It begins with the development of LADM-based country profiles, as listed and discussed in sub-section 4.3.1, referring both to those developed based on Edition I, as well as to the several country profiles that have been developed based on Parts 4 and 5, even though they are still undergoing various phases of the revision process. The final sub-section presents representative LADM implementation approaches and solutions from the geospatial industry.

4.3.1 LADM-based country profiles

ISO (2004) defines a profile as '*a set of one or more base standards or subsets of base standards, and, where applicable, the identification of chosen clauses, classes, options and parameters of those base standards, that are necessary for accomplishing a particular function*.' A profile valid for a whole country is a '*country profile*' (ISO, 2012).

In the development of LADM Edition I, eight country profiles were included, representing Portugal, Queensland (Australia), Indonesia, Japan, Hungary, The Netherlands, the Russian Federation, and the Republic of Korea and are included in Annex D of the IS.

A country profile is an adapted version of the LADM that aligns with a country's specific LA needs and systems (ISO, 2012). Country profiles help in understanding how the tailored LADM profiles can meet local requirements and support the modernisation and integration of LAS with other domains, while they can either describe the current state of LAS and align them with LADM concepts, or they can articulate a vision for future developments and needs in the domain. In this context, LADM should be regarded as a framework for organising spatial and non-spatial data related to (3D) LA spatial units, offering guidelines and principles rather than prescribing a rigid implementation method (Lemmen et al., 2015).

I LADM Edition I profiles

In this scene, multiple countries customise the conceptual model of LADM Edition I as country profiles, to meet the needs and requirements of their LASs. Such profiles require thinking about the future of LA within the country, about its purpose, its new and innovative products and services, its integration with other domains and its benefits to society. International organisation, such as UN-Habitat, FAO, World Bank, etc. support and promote the use and implementation of LADM to worldwide LAS projects.

LASs following a top-down approach, demonstrate the efficient support by the LADM functionality regardless of the registration system that applies to the jurisdiction. Some countries move beyond the conceptual modelling and test their profile with real-world use cases by creating UML instance-level diagrams for the most common or representative LA-cases, as presented in Annex C of the standard (ISO, 2012).

Research has shown (Kalogianni et al., 2021) that LADM country profiles integrate the legal and institutional context governing RRRs with the desired LAS' advancements, where they are developed for various purposes or with specific focus, from different stakeholders (academia, governmental organisations, etc.).

Overall, they can be categorised into two main groups; those applying a holistic approach where all aspects of LA-related information have been mapped, and to those applying focused approach where a specific part of the LA-related information is mapped in an LADM profile (i.e. valuation, underground-objects, marine, etc.). Due to the modular (package) architecture of LADM, countries/ jurisdictions can only use the parts they need to build a country profile.

An overview of LADM-based country profiles, as initially presented by Kalogianni et al. (2021), has been extended and an up-to-date version is presented in Table 4.2.

TABLE 4.2 An inventory of LADM Edition I-based country profiles

#	Country/ Jurisdiction	Relevant publications	Focus
1	Albania	World Bank (2019)	initial steps towards LADM adoption; nationwide
2	Bénin	Mekking et al. (2020)	initial steps towards LADM adoption; nationwide
3	Brazil	Dos Santos et al. (2013)	nationwide
		Paixao et al. (2015)	indigenous tribes' land rights
		Purificação et al.,2019	nationwide; technical implementation
4	Cape Verde	Andrade et al. (2013)	nationwide
5	Chile	Flores-Rozas (2024)	nationwide
6	China	Guo et al. (2011)	nationwide
		Guo et al. (2013)	nationwide; focus on 3D
		Zhuo (2013)	nationwide
		Zhuo et al., 2015	nationwide
		Yu et al. (2017)	immovable property
		Xu et al. (2019)	natural resources
		Zhuo et al. (2020)	farmland
		Xu et al. (2022)	rural homesteads
7	Colombia	Jenni et al. (2017)	nationwide
		Guarín et al. (2017)	nationwide
		Morales et al. (2019)	nationwide; technical implementation
		FAO (2020)	nationwide
8	Croatia	Vučić et al. (2013)	nationwide
		Mađer et al. (2015)	nationwide; linking various registers
		Vučić et al. (2017)	nationwide
		Mađer et al. (2018)	nationwide
		Flego et al. (2021)	marine
		Tomić et al., 2021	nationwide; focus on valuation (LADM Edition II – Part 4)
		Vučić et al. (2022)	nationwide; revision of initial country profile
9	Cyprus	Elia et al. (2013)	nationwide
		Demetriades et al., 2023	nationwide; focus on valuation (LADM Edition II – Part 4)
10	Czech Republic	Janečka et al. (2016)	nationwide
		Janečka et al. (2017)	nationwide; focus on 3D
11	Ecuador	Atapuma et al. (2020)	nationwide
12	Estonia	Batum, 2024	nationwide; focus on spatial planning (LADM Edition II – Part 5)
13	Ethiopia	Kebede et al., 2018	nationwide
14	Finland	Niukkanen, 2023	nationwide

>>>

TOC

TABLE 4.2 An inventory of LADM Edition I-based country profiles

#	Country/ Jurisdiction	Relevant publications	Focus
15	Greece	Psomadaki et al. (2016)	nationwide
		Kalogianni et al. (2014)	nationwide; focus on public property management
		Kalogianni et al. (2015)	nationwide; multipurpose
		Gogolou et al. (2015)	archaeological
		Athanasiou et al. (2017)	marine
16	Guatemala	Koers et al. (2013)	nationwide
17	Honduras	Koers et al. (2013)	nationwide
		José Luis Palma Herrera (2018)	nationwide
18	Hungary	ISO (2012)	nationwide; included in Annex D of Edition I
19	India	Sengupta et al., 2013	initial steps towards LADM adoption; nationwide
20	Indonesia	ISO (2012)	nationwide; included in Annex D of Edition I
		Budisusanto et al. (2013)	nationwide
		Aditya et al. (2020)	nationwide; focus on data acquisition
		Indrajit et al. (2020)	nation – wide; focus on spatial planning and permit system (LADM Edition II – Part 5)
		Indrajit (2021)	nationwide; focus on spatial planning and permit system (LADM Edition II – Part 5)
21	Israel	Felus et al. (2014)	nationwide
		Adi et al. (2018)	nationwide
		Shnaidman et al. (2019)	nationwide
22	Japan	ISO (2012)	nationwide; included in Annex D of Edition I
23	Kenya	Siriba et al. (2013)	nationwide
		Kuria et al. (2016)	nationwide
		Karamesouti et al. (2018)	nationwide
		Okembo et al. (2022)	nationwide
		Okembo et al. (2023)	nationwide
		Okembo et al. (2024)	nationwide; technical implementation
24	Korea	ISO (2012)	nationwide; included in Annex D of Edition I
		Jeong et al. (2012)	nationwide
		Kim et al. (2013)	nationwide
		Lee et al. (2015)	nationwide; focus on 3D
		Kim, Heo (2017)	underground

>>>

TABLE 4.2 An inventory of LADM Edition I-based country profiles

#	Country/ Jurisdiction	Relevant publications	Focus
25	Malaysia	Zulkifli 2014 (PhD)	nationwide
		Zulkifli et al. (2014a)	nationwide
		Zulkifli et al. (2014b)	nationwide
		Zulkifli et al. (2015)	nationwide
		Jamil et al. (2017)	nationwide; technical implementation
		Rajabifard et al. (2018)	nationwide; technical implementation
		Hanafi et al. (2019)	nationwide; technical implementation
		Zulkifli et al. (2019)	nationwide; technical implementation
		Hanafi et al. (2021)	nationwide; technical implementation
		Rajabifard et al. (2021)	nationwide; technical implementation
		Zamzuri et al. (2022)	marine
		Zamzuri et al. (2024)	marine
26	Mongolia	Buuveibaatar et al. (2018)	nationwide
		Buuveibaatar et al. (2022)	nationwide; focus on 3D
		Buuveibaatar et al. (2023)	nationwide; focus on valuation (LADM Edition II – Part 4)
27	Montenegro	Govedarica et al. (2018)	nationwide
		Govedarica et al. (2021)	nationwide
		Radulović et al. (2021)	nationwide; focus on valuation
28	Morocco	Adad et al. (2020)	nationwide
29	Mozambique	Balas et al. (2017)	nationwide
30	Nicaragua	FAO, 2020	initial steps towards LADM adoption; nationwide
31	Nigeria	Babalolaa et al. (2015)	national -3D
		Oyetayo et al. (2017)	nationwide
		Abidoye et al. (2017)	nationwide
32	Pakistan	Ahsan et al. (2024)	nationwide
33	Philippines	Aranas et al. (2013)	nationwide
		Balicanta et al. (2023)	nationwide
34	Poland	Góźdź et al. (2014)	nationwide; technical implementation
		Bydłosz (2015)	nationwide
		Góźdź et al. (2015)	nationwide
		Bydłosz et al. (2020)	nationwide; technical implementation
35	Portugal	ISO (2012)	nationwide; included in Annex D of Edition I
36	Queensland (Australia)	ISO (2012)	nationwide; included in Annex D of Edition I
37	Republic of Srpska	Govedarica et al. (2018)	nationwide
		Govedarica et al. (2021)	nationwide
38	Russian Federation	ISO (2012)	nationwide; included in Annex D of Edition I
		Elizarova et al. (2012)	nationwide; technical implementation

>>>

TOC

TABLE 4.2 An inventory of LADM Edition I-based country profiles

#	Country/ Jurisdiction	Relevant publications	Focus
39	Saudi Arabia	Alattas et al. (2020)	nationwide; only supporting 2D
		Alattas et al. (2021)	nationwide; focus on 3D; technical implementation
40	Scotland	Reid (2019)	nationwide; technical implementation
41	Serbia	Sladić et al. (2022)	nationwide; focus on 3D
		Radulović et al. (2017)	nationwide
		Radulović et al. (2019)	utility networks
		Govedarica et al. (2018)	nationwide
		Višnjevac et al. (2018)	nationwide; focus on 3D
		Bugarinović et al. (2023)	utility networks supporting Augmented Reality
		Radulović et al. (2022)	nationwide; focus on valuation
		Sladić et al. (2023)	nationwide; focus on mass property valuation (LADM Edition II – Part 4)
42	Singapore	Soon et al. (2016)	nationwide
		Yan et al. (2019)	underground
43	Slovenia	Tekavec et al. (2021)	initial steps towards LADM adoption; nationwide
44	South Africa	Tjia (2014)	nationwide
45	South Africa, Johannesburg	Tjia et al. (2013)	focus on the city of Johannesburg
46	The Netherlands	ISO (2012)	nationwide; included in Annex D of Edition I
		Kara et al. (2019)	nationwide; focus on valuation (LADM Edition II – Part 4)
		Van Aalst (2024)	nationwide; focus on core LADM Part 2 and spatial plan information, Part 5
47	Togo	OMCA-TOGO (2024)	initial steps
48	Trinidad & Tobago	Griffith-Charles et al. (2014)	initial steps towards LADM adoption; nationwide
		Griffith-Charles et al. (2018)	juridical, fiscal and marine
49	Turkey	Polat et al. (2018a)	nationwide
		Polat et al. (2018b)	nationwide
		Alkan et al. (2016)	nationwide
		Kara et al. (2018a)	nationwide; focus on valuation
		Kara et al. (2018b)	nationwide; focus on valuation; technical implementation
		Kara et al. (2021)	nationwide; focus on valuation (LADM Edition II – Part 4)
		Gürsoy Sürmeneli et al. (2022)	nationwide; focus on 4D
50	Uganda	Sanjines et al. (2018)	nationwide
51	Victoria, Australia	Aien et al. (2012)	jurisdiction - wide
		Kalantari et al. (2018)	jurisdiction - wide; focus on the spatial part
		Saedian et al. (2022)	jurisdiction – wide; focus on underground
52	Vietnam	Le et al., 2012	nationwide

Apart from the profiles with a nationwide focus on the traditional land-tenure coverage, various LADM-based profiles have been developed for the management and administration of specific domain areas, to name a few: archaeological sites; underground utilities; public (State) property; natural resources; marine space.; agricultural land uses, as listed in Table 4.2. Those applications prove that LADM meets the requirements of law and institutions and supports the achievement of sustainable utilisation of land, air, water and other related natural resources.

From the literature (Kalogianni et al., 2021a; Chipofya et al., 2020), it is evident that the majority of LADM country developments focus on upgrading and modernising existing LASs following a top-down approach. This demonstrates the LADM's efficient support to the design and development of various registration systems. In this respect, there have been few countries that further developed the legal profiles of the standard (Annex F), with most concentrating on the modelling of informal rights.

Among the studies refining LADM RRR classes, Hespanha (2012) (Annex F of ISO 19152:2012) and Paasch (2012) were pioneers in Public and Private Law specialisations of RRR classes. According to Paasch (2012) and Paasch et al. (2015), land use relations fall within the realms of Private Law and Public Law. The Private Law domain generally encompasses relations between individuals regarding the use and ownership of land, while Public Law includes societal regulations (e.g., by the State or municipalities) aimed at achieving the greater good for inhabitants and protecting natural resources or wildlife by regulating unnatural pressure on land. This basic classification of Private and Public Law serves as a foundational basis for describing land use and is instrumental in further refining and developing the LADM legal profiles. The same authors propose specialisations of the LADM's legal profiles, which are also incorporated in ISO 19152-2 (ISO 2025), including:

- an extended profile for privately and publicly imposed rights,
- an extended profile for privately and publicly imposed restrictions (Figure 4.17) and
- an extended profile for privately and publicly imposed responsibilities.

These specialisations enhance the LADM's capability to comprehensively model various legal aspects of land use, thus supporting more effective and inclusive LA practices.

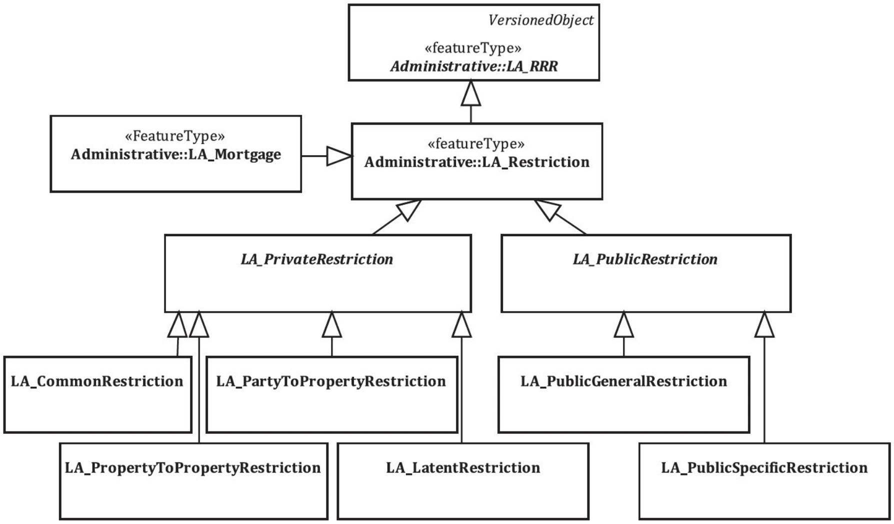

FIG. 4.17 Specialisation of the LADM's LA_Restriction legal profile – extended profile for privately and publicly imposed restrictions (ISO, 2025 and Paasch et al., 2015)

Kitsakis et al. (2021) provide a more detailed and thematic classification of PLRs based on LADM, recognising that PLRs are increasing in number and complexity, necessitating layered and 3D spatial representations. National LASs prioritise different aspects of land management, leading to various types of PLRs that affect LA and hinder the development of a uniform PLR management approach. Legally, variations between jurisdictions stem from differing perceptions of land ownership, where PLRs are viewed as: (a) external restrictions on the absolute power of property ownership; (b) inherent limitations to the nature of ownership; or (c) constraints on exercising ownership rights (Georgiadis, 2012). These characteristics have been considered and Kitsakis et al. (2021) proposed modelling alternatives of PLRs, focusing both on the administrative and spatial packages of LADM.

In addition to the development of country profiles and the refinement of legal profiles, numerous studies have focused on highlighting the modelling of underground objects within LADM Edition I. As a wide range of underground assets exists such as tunnels, utilities (e.g., electricity, communication cables, water supply, drainage, sewage, and gas), train stations, walkways, and basements, with complex geometries and large spatial extents, etc. various studies have been carried out proposing modelling approaches based on LADM, as briefly presented at the paragraphs below.

The development of 3D data models to support Underground Land Administration (ULA) based on LADM have been investigated by various researchers, often in conjunction with 3D data encoding (i.e. CityGML). Saedian et al. (2023) (Figure 4.18) provide an overview of these studies, detailing the specific type of assets, where each study focuses on, the data modelling level (conceptual, logical, physical), and whether a prototype was developed. For instance, Ramlakhan et al. (2023) used IFC (ISO 16739:2018) to register 3D physical data, and LADM to structure the legal data of underground objects, providing a generic mapping from LADM to IFC. A standardised workflow is presented in including of the legal, organisational and technical aspects of modelling the legal ownership interests in a comprehensive approach to tackle the challenges that currently prevent the registration of the RRRs of 3D spatial units below the surface in LASs, based on the LADM.

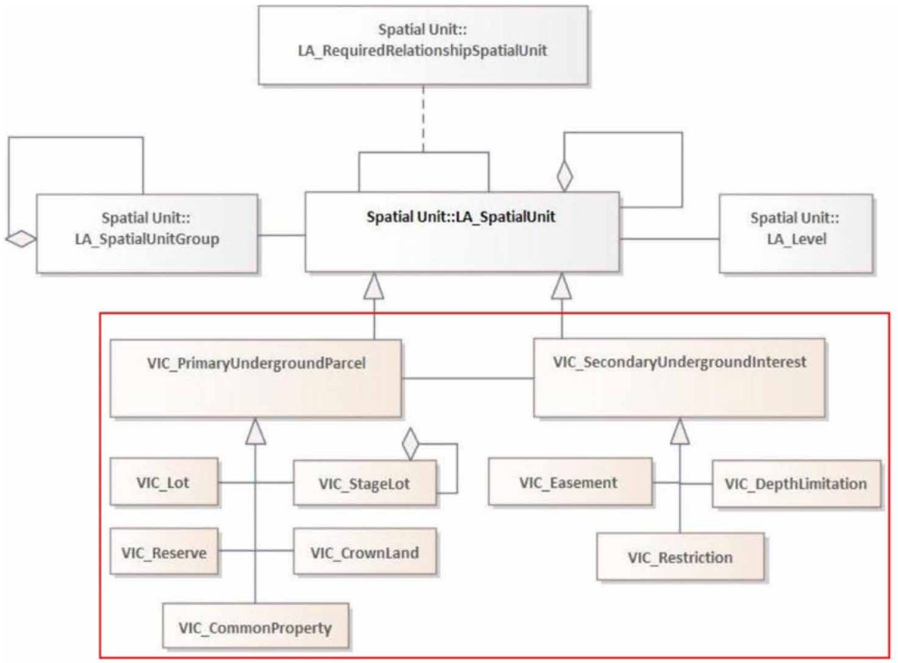

FIG. 4.18 Extension of LADM Spatial Package to model ULA in Victoria, Australia (Saedian et al., 2022)

Saedian et al. (2022) presented an extension to the LADM spatial package to support ULA legal objects in Victoria, Australia. In Victoria, legal spaces are defined independently of the asset types, but there are two types of underground legal spaces defined, primary and secondary parcels, with interrelationships, which are modelled in UML as presented in Figure 4.18.

Finally, Pouliot et al. (2013) used LADM as a comparative tool for evaluating cadastral management systems around the world. Specifically, they examined the spatial representation of condominiums in Quebec, Canada and Alsace Moselle, France. To conduct this analysis, they developed generic country profiles for the two regions and then, the similarities and differences between the systems were identified. The formal description of people-to-land relationships that LADM provides, significantly facilitated this comparison.

II LADM Edition II profiles

While most parts of the second edition of LADM have yet to be published, several studies have explored various parts of this data model (Lemmen et al., 2021). As shown in Table 4.2, seven country profiles have already been developed based on ISO19152-4, and three based on ISO19152-5, with ongoing academic research further contributing to this field.

A notable example is the Dutch country profile of LADM_VM, which is among the first LADM-based profiles for valuation information. It was developed to facilitate all stages of immovable property valuation in the Netherlands, addressing specific data requirements (Kara et al., 2019). Based on the conceptual model, a web-based system has been developed in prototype phase (Figure 4.19). This system employs an LADM_VM compliant dataset to share valuation statistics at various levels (building, building unit, neighbourhood, municipality, etc.) and includes level-specific attributes (Kara et al., 2023b). This prototype showcases the potential for developing local or national valuation systems based on LADM, which can support decision-making processes.

FIG. 4.19 VM_LADM prototype for The Netherlands- floor level implementation (Kara et al., 2023b)

Finally, with the extended scope of LADM Edition II supporting several SDGs, various studies have been carried out to directly or indirectly support' with implementing SDG indicators through a standardised approach, even if not yet implemented in specific countries. Some studies are more qualitative, such as Unger et al. (2023a) that provide a generic framework for LADM as a foundation for supporting SDGs (section 2.2) while Unger et al. (2021) provide further support to women's access to land through LADM. Their study focuses on the specific cases of SDGs 5 – Gender Equality and 2 – Zero Hunger, while presenting the SDG indicators on gender and land detailing how each indicator could impact LADM and proposing queries for reporting and monitoring these SDG indicators worldwide. Moreover, Ahsan et al. (2024), identify crucial SDGs for designing and developing an integrated urban LAS in Pakistan, while presenting the way forward to achieve these SDGs using the LADM-based country profile for Pakistan.

On the other hand, Chen et al. (2024) introduced a four-step method to formalise SDG indicators within the LADM Part 2. Detailed attention is devoted to specific indicators, including 1.4.2 - secure land rights, 5.a.1 - women's agricultural land rights, 14.5.1 - protected marine areas and 11.5.2 - valuation as a basis for direct economic loss. The authors propose procedures for calculating these indicators, introducing blueprints for external classes and interface classes for displaying indicator values specific to countries and reporting years. Specifically, for SDG 1.4.2 their proposed method was implemented by adding new attributes and classes (see Figure 4.20) to the LADM core model to enable direct calculation of this indicator.

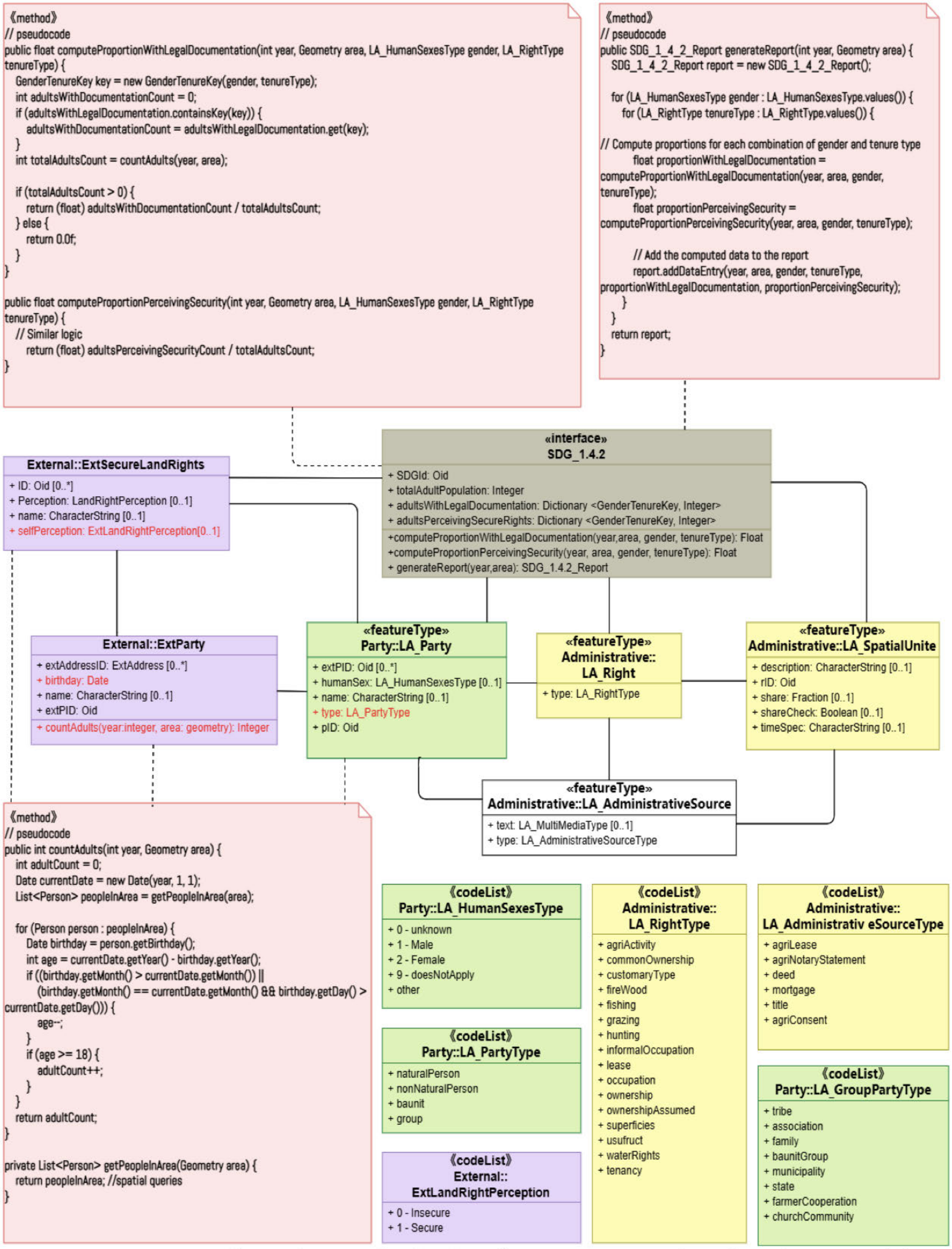

FIG. 4.20 Formalisation of SDG indicator 1.4.2 – secure land rights within LADM Part 2 (Chen et al, 2024)

III LADM profiles' implementations

Some of the creators of the LADM-based country profiles move beyond conceptual modelling towards technical implementation. These implementations often involve developing a country profile and creating a suitable technical model, including database schema, exchange format, and user interface for editing and dissemination.

Examples where LADM is the foundation for software development can be found in Land Equity International/Millenium Challenge Cooperation (LEI/MCC, 2020), where it is stated that LADM compliance is becoming common practice in Land IT systems development. In this respect, Scotland is one of the first countries that has a holistically adopted LADM country profile for the modernisation of Registers' of Scotland using open standards and open-source software (Reid, 2019).

Mađer et al. (2015) propose linking the key LA-related registers of Croatia by extending the LADM and building a relational database management system application. Similar issues and needs to link official registers exist in Serbia, Montenegro, and the Republic of Srpska (Govedarica et al., 2021) and have been addressed by designing a cadastral database based on the country profiles of the three regions, while also developing a desktop and web-software solution based on the principles of MDA and implementing web-services based on the principles of Service Oriented Architecture (SOA). The process model of the Serbian 2D and 3D cadastre has been developed by Sladić et al. (2020), while exploring how IFC can be used to support cadastral workflows, based on a BIM Server. Another study that was carried out using the Serbian 3D LADM-based profile refers to its implementation based on MongoDB (NoSQL database) and Cesium JavaScript library. It was found that a NoSQL database can be used for storing 3D cadastral data defined by a data model based on LADM.

Furthermore, Polat et al. (2018a) developed a web-based archive application for municipal land registry and cadastre transactions, where the LADM conceptual model was used as basis. The application made possible the online exchange and inquiry of information and documents in a digital environment. Cemellini et al. (2018) following a review of existing web-based platforms, developed a system architecture prototype for a 3D LAS for Brisbane, Australia, which focused on 3D data storage and visualisation based on LADM.

In Colombia, there was a need to modernise land records management from their manual and paper-based processes and for that reason the LADM-based profile (named LADM-COL) was developed. The Fit-For-Purpose (FFP) concept was followed (Morales et al., 2019), with a data collection app being developed in collaboration

TOC

with ESRI and Trimble, as well as a public inspection app to communicate the results in a public forum for their approval - both apps are based on LADM. The Colombian profile is based on INTERLIS (Baron et al., 2018) and uses the INTERLIS tools ecosystem (Figure 4.21) for the validation, integration and consolidation of data (called iliSuite) (Jenni et al., 2017; Kalogianni et. al, 2016). INTERLIS is an object-oriented conceptual schema language (CSL), which is being used to define data models in textual form with a rigid computer readable syntax (KOGIS, 2006). LADM and INTERLIS share the same MDA principles (Kalogianni et. al, 2017). Apart from the Colombian, three more LADM- based country profiles have been described in INTERLIS: the profile for a multipurpose cadastre in Greece (Kalogianni et al., 2017), in Switzerland (Kalogianni et al., 2017) and Turkey, for LADM Part 4 (Kara et al., 2018b). Using the INTERLIS tools ecosystem for data validation, as well as the INTERLIS plugin for QGIS software, the implementation of LADM-based conceptual models is facilitated (Kalogianni et al., 2017).

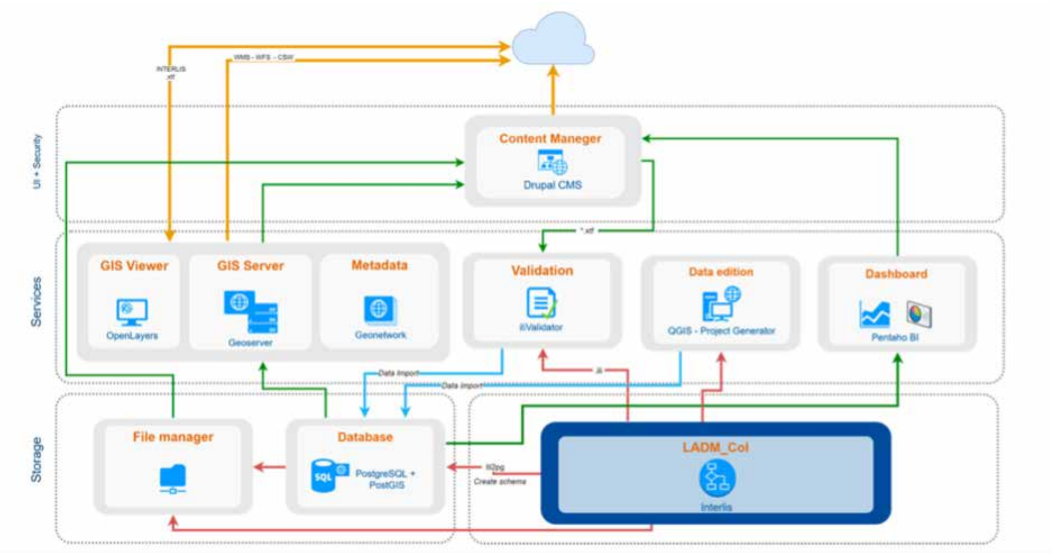

FIG. 4.21 Integration of tools in the web-based system developed for LADM-COL, based on a FOSS architecture and developed with an MDA approach [6] (Morales et al., 2019)

The Kenyan LADM profile (Okembo et al., 2023) is implemented through being its conversion of the UML model to a database, migrating of existing data to the model, developing a web application, configuration of a field data collection application and undertaking the technical test of the field app. Kuria et al. (2016) have developed a web-based LAS aiming to automate the land management transaction processes based on LADM.

Finally, with respect to the developments on the various parts of Edition II, more and more studies go beyond the conceptual modelling. Specifically, Indrajit et al. (2021) developed a proof-of-concept for Jakarta and Bandung, Indonesia, based on Indonesia's LADM country profile for Part 5, enabling the combination of spatial plans with RRR information. Moreover, as illustrated in Figure 4.19, the LADM Part 4 profile for the Netherlands (Kara et al., 2023b) has been implemented in a web-based system to share valuation statistics in each one of the levels, while allowing spatial, physical, thematic and temporal characteristics of 3D valuation units.

IV STDM profiles

The STDM has been implemented in various contexts to support the engagement of communities with land authorities and to address specific LA needs. Notable implementations include the following, as listed below and presented in Figure 4.22[24]:

- **Urban Informal Settlements:** STDM has facilitated community engagement with land authorities to prioritize urban services in areas such as Mbale, Uganda; Mashimoni in Nairobi; Mnanzi Mmoja in Mombasa, Kenya; and Ciudadela Sucre in Soacha, Colombia. It has also been used for settlement profiling to inform city planning initiatives in several municipalities in Uganda. Moreover, STDM was used to document tenure rights of urban poor in Namibia.
- **Peri-Urban Communities:** In the Mungule Chiefdom in Zambia, STDM has been used to address gender aspects of customary tenure.
- **Rural Agricultural Activities:** STDM has been applied to assess farming land acreage by smallholder farmers in Kalangala, Uganda.
- **Land Mediation:** In Luhonga, North Kivu, in the Democratic Republic of Congo, STDM has been used to record land mediation efforts.
- **Claims recordation:** land and conflicts of in Lebanon and Iraq.
- **Other STDM implementations** (Unger et al., 2023b)**:** Jordan, Lao People's Democratic Republic, Libya, Palestine, South Sudan, Syria, Tunisia, Yemen and Zambia.

24 https://stdmupdate.gltn.net/applications/

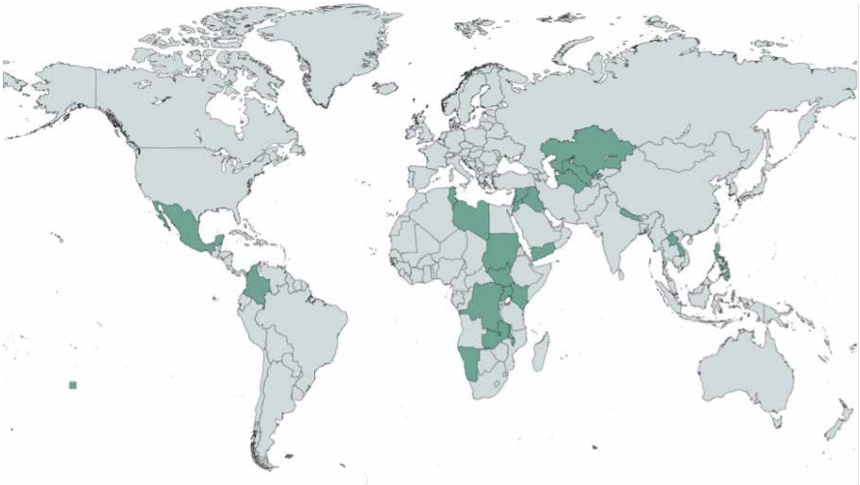

FIG. 4.22 STDM implementations around the world

4.3.2 LADM-based software solutions

The previous sub-sections demonstrated the extensive adoption of LADM Editions I and II, as well as the implementations of STDM, all at conceptual level, or through the development of prototype or real implementations and applications, which are usually country specific.

Beyond academic and conceptual advancements, industry-driven initiatives have sought to develop LADM-compliant solutions to streamline LA processes. The adoption of a common language within industries has long been a successful practice in GIS (referring to the standardised terminologies, data models, and protocols), facilitating standardised workflows and improving interoperability. As technology advances, the demand for a widely accessible, common industry language continues to grow (Smyth, 2019).

LADM serves as a unifying framework for the LA community, ensuring consistency in data representation and exchange. However, despite progress in geo-ICT, a gap persists in the development of tools that can model people-to-land relationships independently of their formalisation or legality. This limitation underscores the need for enhanced LADM and STDM-supporting solutions that address both formal and informal tenure systems.

ESRI has made important contributions to the implementation of the LADM through its ArcGIS platform, taking LA beyond field data collection and management by enabling data sharing among organisations and with the public (Bar-Maor et al., 2022). Specifically, the ArcGIS Parcel Fabric supports LADM principles and provides a scalable, interoperable tool for LA. It includes advanced parcel editing and managing tools and capabilities for integrating web services to expose information and metadata, in both a multiuser and single-user environment. It is based on SOA and includes built-in, configurable quality control measures to ensure data accuracy and reliability. ESRI has mapped the Parcel Fabric to LADM (Figure 4.23) using the LADM abstract test suite, where several gaps between the Parcel Fabric and LADM have been identified, requiring improvements and enhancements. Despite the needed changes, Bar-Maor (2022) claims that an LADM-compliant schema can be either directly created by creating a new parcel fabric or by importing an LADM-based XML Workspace document.

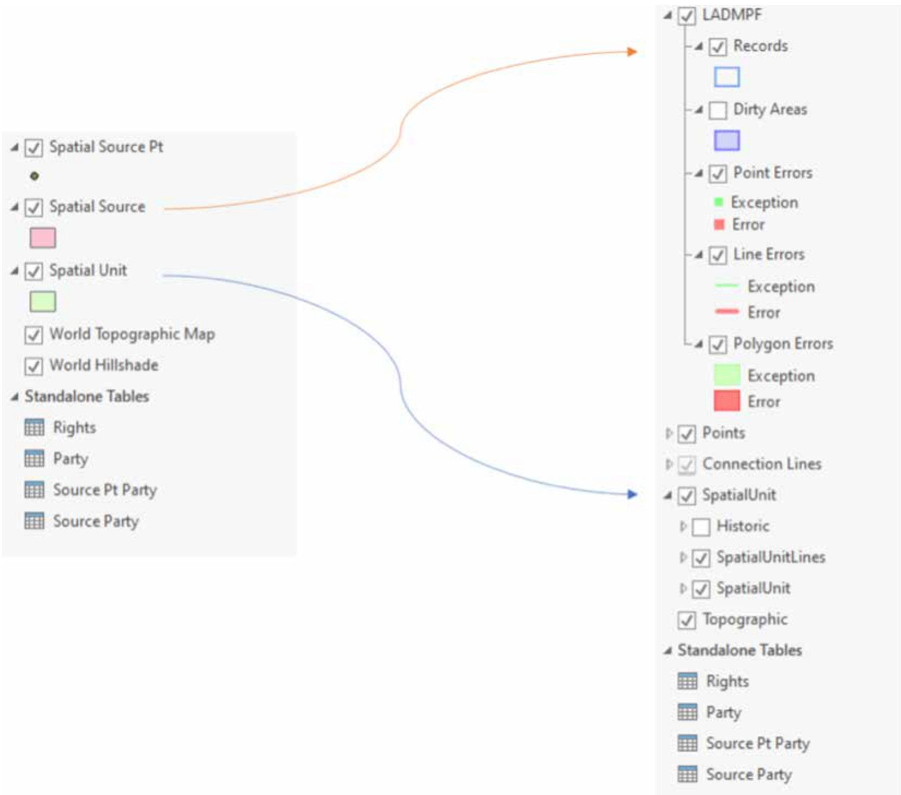

FIG. 4.23 Proposed migration of LADM Spatial Source into the Parcel fabric record and LADM Spatial Unit as Parcel Type (ESRI, 2024)

The ArcGIS Collector app has been used for field surveying in the context of the project of LAS modernisation in Colombia that was introduced in the previous sub-section. The field surveying was conducted by locals, usually landowners, under the supervision of professional surveyors. The locals walked around their parcel to document its boundary, capturing the GPS information for each location that comprised the parcel by using the app. GPS information for each point is captured automatically while the parcel boundary is collected and stored based on LADM structure (Morgenthaler, 2020).

Moreover, GEOFIT IGN FI has been instrumental in implementing the National Land Information Systems (NLIS) in Uganda and Tanzania through several projects, that have successfully established reliable LA services and improved public confidence in LA (Lemmen et al., 2020). This technology solution has been branded as “Innola® framework”, adheres to industry standards such as the LADM, OGC, and W3C, ensuring a structured and standardised approach to LA. The systems have enhanced the reliability, security, and public confidence in LA services, showcasing best practice models for future projects. Specifically, key features include:

- **Customisation and extensibility:** The framework is customised according to country-specific information content, establishing a national LA profile adhering to the LADM standard.
- **Integration and validation:** The system integrates data digitisation, migration, and maintenance processes with the overall enterprise-wide business processes. This ensures that data is validated and consolidated in real-time, while being compliant with LADM.
- **Agile development:** Early involvement of customer stakeholders in the agile development cycles helps minimise technological and operational risks.

In the GIS industry, a STDM plugin for the open-source software QGIS has been developed. All the spatial and attribute information in the STDM is stored in a PostgreSQL/PostGIS database, with the user interface hosted as a QGIS plug-in.

LADM has been used as a reference for data collection in land registration activities through mobile apps dedicated to land tenure mapping that have been developed either by industry or by international organizations. Namely, Trimble supports both LADM and STDM via the Trimble Penmap field data collection software. Trimble’s FFP solution for LA supports field survey and GIS data collection in line with legal data collection. When it comes to land registration tools, the open-source software Solutions for Open Land Administration (SOLA) (FAO, 2020; 2024) that consists of several tools that supports LA functions is based on LADM. SOLA desktop applications consist of the following tools: Registry (land rights registration and cadastre); systematic registration (data collection and public display); state land (state land management), and open tenure (informal land records). The data models maintained by SOLA applications are at least Level 1 compliant with LADM, while some of the packages are Level 2 or Level 3 compliant (COWI, 2018).

SOLA has extended the data model of LADM (e.g. regarding workflows, transactions and processes). An application with functionality comparable to SOLA Open Tenure is the Mobile Applications to Secure Tenure (MAST[25]). MAST is an USAID development for tools that use mobile devices and a participatory approach to map and document land and resource rights (COWI, 2018). The MAST application provides a suite of tools to support the collection and management of land rights information, including a mobile application to capture land rights information in the field and a back-end land rights data management application with tools to manage an inventory of land information. USAID (2016) states that for a project in Tanzania MAST used the STDM to configure attributes required for rural land adjudication.

Similarly, the participatory land registration (PaLaR) method in Indonesia's rural areas, focusing on data quality, cost, and time supports the collection of spatial and legal data (Aditya et al., 2020). Data was collected digitally using a tablet with the Meridia Collect App, connected to a GNSS antenna. On the backend, the app was supported with Podio to support the online data management, and to cover data quality checking. Moreover, Aditya et al. (2021) developed an LADM-based data collection tool, which focuses on capturing a land parcel and its link to a related tenure claim. The app is developed using OGC's GeoPackage to store spatial and administrative sources while accessing national cadastral and civil registry databases.

Finally, without initiation from the industry, but with a close relation to it, an OGC best practice document on UML to JSON encoding rules has been released (OGC, 2024a). It has not been used for LADM implementation, as it is a recent update, however it seems promising, as the aim is to come to a standardised encoding from UML to JSON implementation (including plain JSON, GeoJSON and JSON-FG).

25 https://www.land-links.org/tool-resource/mast-technology/

4.4 Summary

Answering **Sub-RQ1b "What is the current state-of-the-art in standardisation in (2D and 3D) Land Administration around the world, as progressed by standardisation organisations?"**, this chapter provides a concise overview of the ISO 19152:2012 LADM, detailing its key concepts and implementations since its adoption as an IS in 2012. It also underscores the ongoing evolution of the model, in response to emerging challenges and advancements in LA. Focusing on developments up to early 2024, the chapter encompasses the standard's revision process, and the developments related to the various parts of the second Edition.

The chapter addresses a critical gap in conventional LAS: between formally documented, registered land rights and customary and informal tenure. This gap has been effectively addressed by LADM and its specialisation STDM, both of which are analysed in this chapter. The integration of STDM within LADM underscores the model's commitment to inclusivity, providing a robust framework that caters to diverse socio-economic settings and contributes to reducing tenure insecurity in regions with significant numbers of informal settlements. Additionally, LADM's alignment with global frameworks underscores its critical role in promoting effective and equitable LA practices worldwide.

LADM has evolved since its inception, integrating with various IS, guidelines, and frameworks to enhance its applicability and effectiveness. The development of numerous LADM-based country profiles demonstrates the standard's flexibility and ability to support different LAS needs worldwide. The chapter features an inventory of these profiles showcasing the extensive adoption and adaptability of LADM. This inventory serves as a valuable resource for countries and researchers aiming to establish or enhance their own LAS and provides a repository of knowledge for understanding the global landscape of LA.

Additionally, this chapter explores various implementations of LADM, whether based on country profiles or initiated by the industry. It reviews advancements in technology, policy, and practical developments that have influenced LADM applications, providing case studies and examples from different jurisdictions to illustrate how LADM has been adapted to meet specific national or regional needs.

Moving forward ISO's ongoing revision of LADM ensures that the standard remains responsive to evolving user requirements. The decision to refine and expand the scope of LADM Edition I reflects feedback from the global LA community. LADM Edition II marks progress, incorporating comprehensive attributes of land value, use, and development, and addressing technical and practical needs through refined packages and new parts.

The new Edition is organised into six parts, allowing for targeted updates and revisions. A requirements-based approach streamlines the development process, enhancing quality and relevance, and providing stakeholders with powerful tools to ensure compliance and effectiveness. Parts' 1 and 2 backward compatibility facilitates a smooth transition from the earlier Edition to the second one, safeguarding existing developments.

LADM Edition II extends support to marine georegulation, property valuation, and spatial planning, making its coverage of LA more complete. Attention is particularly drawn to Part 6 – Implementations, highlighting the need for encodings to assist the implementing community. The operationalisation of LADM creates opportunities for LA service providers and vendors to offer innovative products and services, enhancing the efficiency of LA-related organisations. LADM Edition II further supports 3D implementation, with developments like the refined survey models, new types of spatial units, and 3D spatial profiles, ensuring comprehensive support for modern LA needs.

In conclusion, the advancements in LADM from Edition I to Edition II, along with practical implementations and country-specific adaptations, illustrate the model's pivotal role in shaping modern LA practices. This chapter provides a solid foundation for understanding the importance of LADM in the global context.

To answer **Sub-RQ4a "Which are the cadastral surveying requirements?"** this chapter presents a structured overview of the key cadastral surveying requirements outlined in Part 2 – Land Registration of LADM Edition II. These requirements ensure that cadastral data is maintained in a distributed, standardised, and transparent manner while supporting multiple organisations, dynamic updates, and historical traceability. A fundamental principle reflected is the avoidance of data duplication, achieved by keeping LA data at its source. This is enabled through integration within a Spatial Data Infrastructure (SDI), where authoritative datasets are maintained by custodians and shared across systems, ensuring consistency, authenticity, and interoperability. This approach enhances interoperability and data integrity by ensuring that updates and transactions are made in real-time at authoritative sources rather than relying on redundant copies. The emphasis on authentic source documents (Requirement 2-6) and traceable updates (Requirement 2-7) further supports data reliability, historical transparency, and accountability, with each transaction being linked to a responsible person (Requirement 2-8). These aspects strengthen the governance of cadastral systems by ensuring clarity in ownership, land rights, and historical modifications, which is essential for dispute resolution, legal compliance, and efficient land transactions.

The representation of spatial units (Requirement 2-12) with unique identifiers (Requirement 2-13), ensuring seamless integration and data consistency, is one of the key requirements proposed. This requirement acknowledges the diverse forms of spatial units, which can range from text-based descriptions to detailed 3D representations. The cadastral reference system (Requirement 2-16) ensures that surveys and cadastral data are accurately georeferenced, supporting various surveying methods (Requirement 2-15) that differentiate between legal and physical boundaries. The quality of cadastral data (Requirement 2-17) is a critical aspect, ensuring that information is reliable, complete, and accessible while allowing for future improvements and metadata documentation.

These cadastral surveying requirements formally introduced in late 2022 as part of the Committee Draft (CD) and Draft International Standard (DIS) stages of LADM Edition II. These requirements were refined through balloting and feedback from participating countries in 2023, ensuring their alignment with international LA needs.

This structured approach highlights how LADM Edition II enhances cadastral survey workflows by incorporating standardisation, interoperability, and adaptability, ultimately ensuring that LASs remain robust, scalable, and efficient in addressing the evolving complexities of land administration worldwide.

PART II

3D spatial units and sources

5 The Spatial Development Lifecycle of Built Environment and Spatial Units

[Sub-RQ3a] **What are the main types of 3D spatial units based on the complexity of their geometry?**

This chapter is based on the following publications:
Kalogianni, E., *Dimopoulou, E., Thompson, R.J., Ying, S., van Oosterom, P.J.M. (2020). Development of 3D spatial profiles to support the full lifecycle of 3D objects. Land Use Policy, 98, 104177. doi: https://doi.org/10.1016/j.landusepol.2019.104177*
Kalogianni, E., *Dimopoulou, E., Thompson, R.J., Lemmen, C.H.J., van Oosterom, P.J.M. (2018). Investigating 3D spatial units as basis for refined 3D spatial profiles in the context of LADM revision, In Proceedings: 6th International Workshop on 3D Cadastres, pp. 177-199.*
Kalogianni, E., *Gruler, H.C., Bar-Maor, A., Harold, B., Lemmon, T., Lemmen, C.H.J., van Oosterom, P.J.M. (2022). Investigating the Requirements for the ISO 19152 LADM Survey Encodings. In Proceedings: 10th International FIG Workshop on the Land Administration Domain Model, pp. 53-66.*
Kalogianni, E., *Dimopoulou, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2020). BIM/IFC files for 3D real property registration: an initial analysis. In Proceedings: FIG Working Week 2020, pp. 1-22.*
Broekhuizen, M., ***Kalogianni, E***., *van Oosterom, P.J.M. (2025). BIM/IFC as Input for registering apartment rights in a 3D Land Administration Systems - A Prototype Webservice. Land Use Policy, 148.*

ABSTRACT The potential for reusing information within the Spatial Development Lifecycle (SDL) is an important driver of the economic value of geospatial information. The SDL encompasses stages from planning and construction to maintenance and decommissioning, with digital technologies facilitating data interoperability and reuse across these stages (as detailed in section 5.1). Addressing challenges related to data sharing and integration can enhance the effectiveness of the SDL by establishing an efficient and organised data flow grounded in standards (as outlined

in Chapters 3 and 4), ensuring that spatial information remains a valuable, enduring asset that supports both social and economic progress throughout its lifecycle. Spatial units registered to LAS worldwide, vary from 2D to complex 3D, shaped by available data, regulatory frameworks, and market demands (Thompson et al., 2017), with a revised taxonomy presented in section 5.2. Depending on the type of spatial units, data from different sources can be used, with a focus on reusing design-phase information in LA. In this scene, adoption of international standards like LADM for LA and IFC for BIM supports compatibility and reusability. This integration supports comprehensive 3D representations of land and property, and addresses challenges in standardisation, data quality, and interoperability. International research and projects showcase BIM/IFC alignment with LA requirements, establishing frameworks for managing complex spatial units, like volumetric and underground assets, as presented and discussed in section 5.3. Additionally, land survey data, including requirements for standardised survey encodings (intended for LA registration) are detailed in section 5.4. The chapter concludes with a Discussion section (5.5), which provides a summary of the key topics and addresses key considerations for effective SDL data governance.

5.1 Lifecycle thinking for 3D LA

5.1.1 Stages of the Spatial Development Lifecycle (SDL)

The Spatial Development Lifecycle (SDL) encompasses the management of built environment and spatial units through various stages such as zoning, surveying, designing, financing, permitting, constructing, registering, valuating, maintaining, operating, decommissioning and redevelopment or renovating. This lifecycle is not confined to existing structures, such as buildings, but also applies to those that are in the design phase, as well as natural resources like forests, air and marine spaces, and infrastructures including underground utilities. Within the SDL, LA plays a central role, especially in the registration phase, where it ensures both legal and spatial clarity for land and property. However, its impact also extends beyond registration, influencing multiple phases of the lifecycle.

One major challenge in the SDL is data fragmentation, as different stakeholders—such as those in the AECOO sector, GIS professionals, and financial institutions—employ a variety of systems and methodologies. This fragmentation leads to technical, legal, cultural, and business barriers, which hinder effective data exchange throughout the lifecycle. As a result, data silos form, leading to data loss, redundancies, and inconsistencies. Poor coordination also limits the reuse of data, negatively affecting its quality and consistency across SDL stages.

Other key concerns are the source, quality, and dimensionality of data, especially since it is provided by the design stage or gathered from multiple providers using technologies like laser scanners, Unmanned Aerial Vehicles (UAVs), and Global Navigation Satellite Systems (GNSS). Ensuring that datasets are discoverable, shareable, and of high quality across all lifecycle stages is crucial. Adding to this complexity is the reuse of data from other sources (i.e design), like BIM models, which shall meet quality standards and be evaluated against parameters such as completeness, consistency, positional accuracy, and thematic accuracy, in line with international standards (ISO, 2013). Data often appears in 2D formats, lacking height/ depth information or presenting it as an attribute rather than an independent coordinate, resulting in ambiguities. Additionally, the status of the data—whether it reflects the as-built or as-designed—often remains unclear, while crucial information on versioning and history may be missing.

A wide range of stakeholders is involved in LA activities, including governmental agencies (land registries, planning authorities, tax authorities), engineers (surveyors, architects, contractors), real estate developers, legal professionals and notaries, financial institutions, NGOs, landowners and software or hardware providers, as well as other LA-related authorities. What is more, international organisations (WB, UN, etc.) are also involved in these activities. These stakeholders influence LA policies and practices, each with specific interests in land use and governance. The integration of 3D datasets into SDL processes plays an increasingly significant role in decision-making and governance across sectors like architecture, spatial planning, and LA. As 3D datasets become more widespread, stakeholders will likely become data producers, requiring governance strategies that include both bottom-up and top-down approaches.

Collaboration across sectors, especially in LA, promotes data harmonisation, minimises inconsistencies, and facilitates data reuse throughout the lifecycle. Spatial Data Infrastructures (SDIs) can facilitate data sharing, reduce duplication, and improve sustainability and transparency by fostering circular data flows between stages. This approach facilitates the reuse of data generated in one stage (e.g., design) in later stages (e.g., spatial planning, permitting, LA), creating external connections between departments and sectors to support interoperability. For example, data collected during the design and construction of a building—such as 3D models, permits and financial/ taxation records—can later be re-used for operations, maintenance, and LA, maximising its value across the lifecycle.

The re-use of data in 3D LAS provides benefits, including more efficient data management through lifecycle data reuse, which reduces the need for repeated data collection and minimises costs, time, and errors. Additionally, improved interoperability by integrating data from various sources like BIM and GIS allows for better collaboration among stakeholders, ensuring the use of unified and accurate information across the SDL.

5.1.2 Digital Technologies though SDL

The integration of digital technologies into the SDL addresses key critical challenges by enhancing process efficiency. One of the key barriers to achieving effective data circularity is the lack of interoperability between data and stakeholders. Addressing this issue requires the adoption of more structured and standardised approaches to improve data flow and interoperability, which can significantly increase the overall efficiency of the SDL.

Digital technologies, especially when aligned with international standards such as BIM, GIS, and ISO/OGC standards, enable the reuse of data (Çetin et al., 2021), optimising workflow management and decision-making across all phases of the SDL. Specifically building passports or Building Logbooks (EC, 2023b), BIM, (3D) GIS platforms (such as Digital Twins) and data acquisition technologies receive great attention, as they play a key role in various stages of the SDL.

Figure 5.1 presents the stages of SDL, as well as the Digital Technologies involved in each stage. Building Passports play a critical role in this process by serving as comprehensive digital records that track a building's lifecycle from planning and construction to decommissioning. A Building Passport is a digital, lifecycle repository that consolidates all administrative, spatial, technical, functional, and performance-related information about a building, serving as a central access point for both static 'as-built' data and continuously updated records (Hartenberger et al., 2021). They capture essential legal, technical, and operational data, supporting the seamless integration of 3D LAS, especially when used complementary to BIM. Meanwhile, BIM enhances 3D LA management by providing detailed, structured data across the various stages of the SDL. During surveying and data collection, BIM complements traditional techniques or facilitates scan-to-BIM workflows, ensuring consistency between physical assets and their digital counterparts. In the design phase, BIM could integrate legal information, while throughout construction, it tracks structural changes.

During decommissioning or redevelopment, BIM documents the building's state and updates relevant registries accordingly. Further discussion on how BIM contributes to 3D is presented in section 5.3.

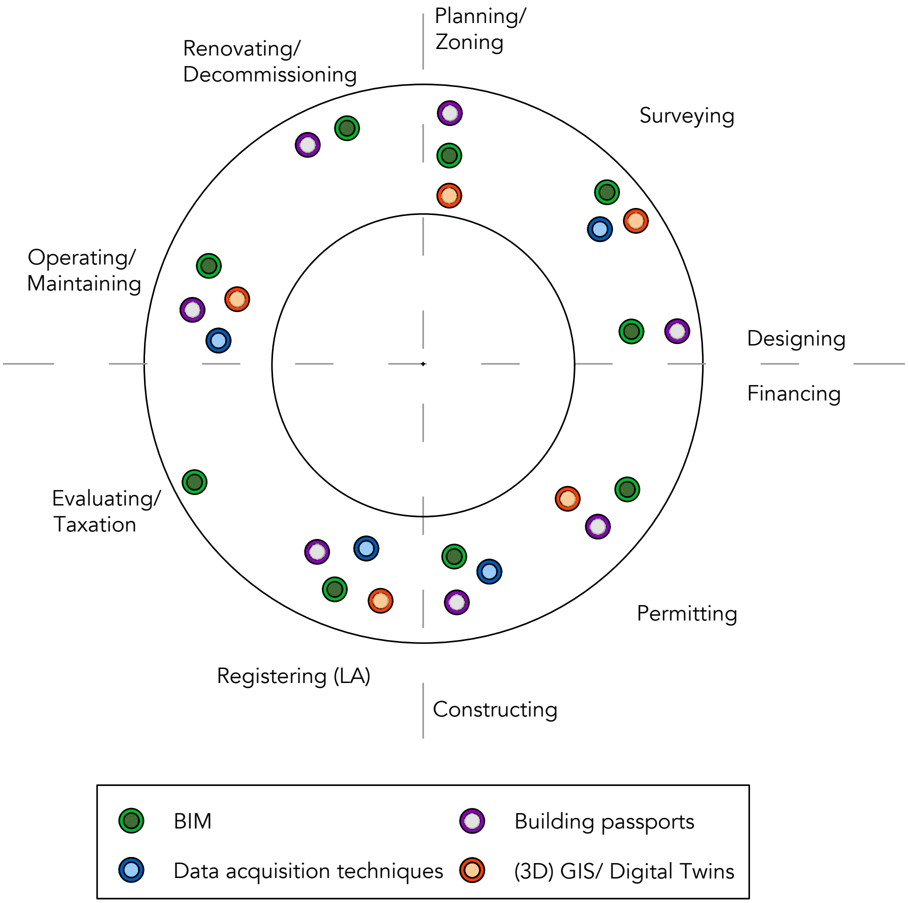

FIG. 5.1 Stages of Spatial Development Lifecycle and Digital Technologies throughout SDL

Various data acquisition technologies further enhance the data reuse across the SDL. Unmanned Aerial Vehicles (UAVs) provide high-resolution aerial imagery and 3D mapping capabilities for surveying, planning, and construction monitoring. Global Navigation Satellite Systems (GNSS) offer precise geolocation for land and built assets, while remote sensing services offer tracking land use patterns and environmental monitoring. LiDAR technology captures detailed terrain and building data, which is essential for creating high-precision 3D models of land, buildings, and underground utilities, crucial for LA and spatial analysis.

The integration of use of 3D GIS and Digital Twins represents an advancement in LA, by providing comprehensive, dynamic views of spatial units, allowing for the accurate visualisation and analysis of land, buildings, and infrastructure. By combining real-time data with historical and projected information, 3D GIS and Digital Twins support informed decision-making in zoning, property registration, and land use management. Digital Twins offer real-time monitoring and updates of physical assets, facilitating efficient planning, construction, and maintenance processes, and enabling more transparent and accurate land governance.

In this context, the integration of BIM and 3D GIS has gained increasing attention for addressing urban planning, information management, and 3D LA challenges. However, the quality of BIM data shall be carefully assessed before integrating it with 3D GIS to avoid potential uncertainties.

In conclusion, the integration of digital technologies and the adoption of international standards are essential for overcoming challenges related to data interoperability in the SDL. These technologies facilitate better data sharing, lifecycle management, and governance, ultimately leading to more transparent, efficient, and sustainable land and property management throughout the SDL.

5.2 3D Spatial Units: selected use cases and taxonomy

Spatial units registered in LASs, which range from simple2D representations to more complex 3D representations of spaces worldwide, are defined at varying levels of complexity based on available data, regulatory frameworks, and market demands (Thompson et al., 2017). While 3D spatial units can appear complex, they are often composed of simpler geometric forms, with many being prisms derived from the vertical extrusion of 2D polygons (Thompson et al., 2016a). These differences call for different approaches in terms of surveying, data storage, registration, maintenance, visualisation and dissemination. Subsequently, this asks for the categorisation and organisation of the different types of spatial units that are identified and legally recognised and applicable across various jurisdictions worldwide.

5.2.1 Real-world use cases of 3D spatial units

The categorisation of 3D spatial units often begins with real-world use cases, reflecting the specific requirements and characteristics of different jurisdictions. By grouping similar use cases, spatial profiles can be modelled more effectively. In this Section, the focus is on use cases from Australia, China, and Greece.

In Australia, cadastral spatial units were historically viewed as 2D parcels, with ownership extending from the earth's centre to an infinite distance above the surface. Over time, specific rights for subterranean properties, such as mines, were recognised. In the late 20th century, "strata titles" were introduced in Australia (referring to units within buildings with the properties defined by the building structure), followed by volumetric spatial units, which are defined independently of any structures. These units have the same legal standing as 2D parcels.

In Australia, the legal treatment of 3D spatial units is simplified by applying the same principles for 2D spatial units under property law. This legal framework allows volumetric spatial units to be subdivided into smaller individual units, each governed by a strata title, reinforcing the concept of "3D spatial units within 3D spatial units". This approach is particularly useful for managing complex infrastructure and building projects. A key feature of this system is the creation of "common property," which refers to the representation in a volume remaining after individual units have been excised. This is especially relevant in large, intricate developments such as the Soleil Building in Brisbane illustrated in Figure 5.2. The building is one of the tallest in Brisbane and is divided into four volumetric lots, with one specific lot subdivided into floors, each containing seven building unit lots and common property. These volumetric lots are complex, but the individual units are defined by the walls, forming simple slices.

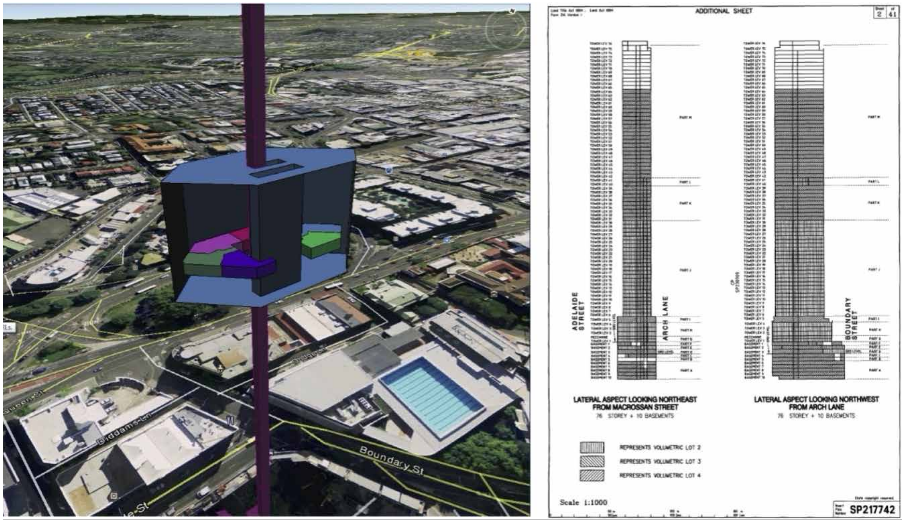

FIG. 5.2 Soleil building in Brisbane in 3D representation and its 2D cross-section (Kalogianni et al., 2020)

In recent years, Shenzhen, China, has seen significant advancements in 3D LA applications, including three primary types of 3D spatial units: standard space blocks, underground properties, and complex collections of volumetric spatial units. These cases illustrate the growing complexity of 3D LAS, requiring a tailored approach to legal frameworks and geometric space modelling. A representative example is shown in Figure 5.3, which highlights a complex property collection across different elevations, comprising five distinct 3D volumetric units: a metro station, a metro tunnel, and both underground and above-ground commercial properties. This complex system is further emphasised through its representation on a 2D cadastral map, showcasing the enhanced clarity and utility provided by 3D registration and visualisation in managing cadastral data.

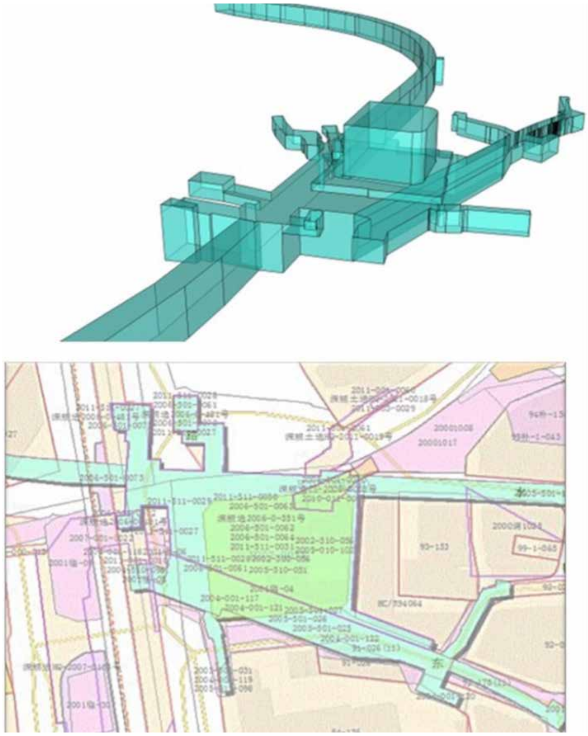

FIG. 5.3 Collection of volumetric property units in Shenzhen, China (Kalogianni et al., 2020)

A notable use case from Greece involves 3D cadastral registration for infrastructure, specifically a subway station. Figure 5.4 presents a longitudinal section of a subway station along Thessaloniki's Metro Line 1, which is currently under construction (Kitsakis et al., 2017). This case showcases the complex nature of 3D spatial units in urban infrastructure projects, emphasising the need for precise modelling and legal frameworks to manage overlapping properties and infrastructure effectively.

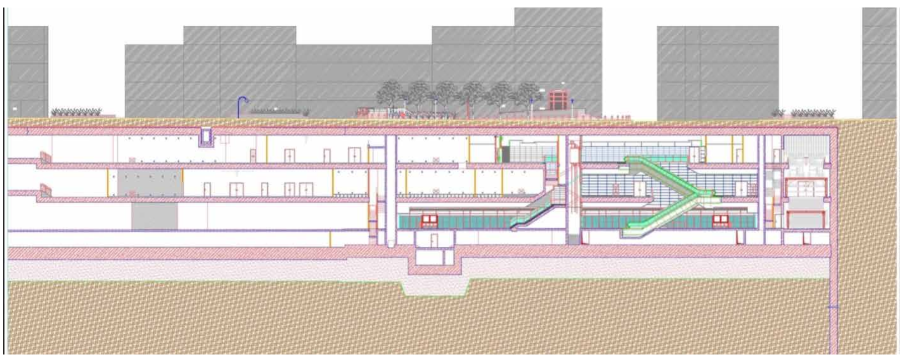

FIG. 5.4 Longitudinal section of subway station, in Thessaloniki, Greece (Kitsakis et al., 2017)

5.2.2 A taxonomy of 3D spatial units

Van Oosterom et al. (2011; 2014) and Thompson et al. (2015; 2016a; 2016b) have studied the variety of spatial units in use, globally and developed a classification system. Based on it, spatial units are categorised as "2D Spatial Units," "Above/Below a Depth or Height" (semi-open spatial units), "Polygonal Slice," "Single-Valued Stepped Slice," "Multi-Valued Stepped Slice," and "General 3D Parcels." This categorisation initially based on Queensland, Australia's use cases, helps in defining how spatial unit information should be represented and stored. The complexity of a spatial unit's physical shape—e.g., number of bounded faces or volume types—affects the modelling and technical specifications of spatial profiles and encodings.

Additionally, the definition of boundaries varies across jurisdiction; for example, in the UK, boundaries are often tied to topographic objects, while in the Netherlands, boundaries are described by coordinates derived from surveys. These differences must be accounted in spatial profiles' development (see section 6.1), with clear references to topographic objects or 3D boundaries. This initial taxonomy has been further refined and expanded by Kalogianni et al. (2018), enhancing its application in global LASs.

Spatial units are generally classified into two main categories: 2D and 3D spatial units (FIG, 2018b; Thompson et al., 2016a). A 2D spatial unit (Figure 5.5 A) is defined by the 2D location of points along its boundary, with five spatial profiles developed to describe for this type, as outlined in Annex E "Spatial units and spatial profiles" of ISO 19152 LADM (ISO, 2012). These units are the most common across many jurisdictions and actually imply 3D spatial units, as they define a vertical prism extending above and below the surface without explicitly bounded horizontal faces (Stoter and van Oosterom, 2006). Although those units are the simplest to store, visualise, and manage administratively, they pose challenges in 3D visualisations due to their open nature at the top and bottom.

In contrast, 3D spatial units, which are explicitly defined by bounding faces and 3D points, provide a clearer, closed definition of the volume they occupy, making them more appropriate for 3D visualisation and applications. The 3D spatial units are categorised into sub-groups based on their complexity. This classification, based on their geometric complexity and the complexity of the legal reality that has to be represented, helps to streamline the management, storage, and visualization of these units within LASs.

These sub-categories are organised in an order of increasing complexity:

- **Semi-open spatial units (Above/Below a depth or height):** Defined by a 2D boundary with either an upper or lower horizontal plane. These are simple to manage and visualise in a 2D sense; a 2D spatial unit with a height limitation attribute. However, they present challenges in 3D visualisation due to their un-closed nature. Specifically, for an individual spatial unit of this category the information required is: the extent of the 2D shape; the definition of a horizontal surface (upper or lower) and the definition of the surface relation (unit is above or below the land surface). They usually represent spaces such as mining areas or air rights.

- **Polygonal slice spatial units:** These are 2D polygons with both top and bottom horizontal surfaces, the most common form of closed 3D spatial unit, commonly used for the representation of simple cadastral boundaries due to their simplicity in both storage and visualisation. Specifically, for an individual spatial unit of this category the information required is: the extents of the 2D shape; the definition of a horizontal surface (upper or lower) and the definition of the surface relation (unit is above or below the land surface). They usually represent spaces such as mining areas or air rights.

- **Single-valued stepped spatial units:** These units consist of multiple horizontal and vertical boundaries, non-self-overlapping in the vertical dimension, as each one maintains a constant z-value, giving the appearance of a stepped polygon. Such spatial units are easy to visualise in 2D and are well-suited for scenarios where vertical boundaries are straightforward and non-overlapping in the z-dimension.

- **Multi-valued stepped spatial units:** These units allow for more complex volumes, as they are defined by a set of boundary faces (either horizontal or vertical), allowed to have a different z-value, like tunnels or caves.

- **General 3D spatial units:** Spatial units not fitting into one of the earlier categories are classified into this category. They represent the most complex cases, with boundaries that are not exclusively vertical or horizontal, accommodating irregular shapes and forming multi-faceted 3D volumes, used for representations of intricate urban environments. This category may require further classification as the following boundaries fall under it: 2-manifold, planar/curved boundaries, open/closed volume, single/multi-volume. It should be considered whether the sub-categories created will be mutually exclusive, or if they will represent independent aspects that could lead to multiple categories based on their possible combinations.

- **Building/construction format spatial unit:** These are defined by the extents of an existing or planned structure that contains/will contain the unit, and they are particularly common in urban environments. This is the most prevalent category of 3D spatial units in places like Queensland, Australia, and in other countries.

Depending on local regulations, some jurisdictions may choose not to record the geometry of such units. In these cases, the spatial unit can be represented with a "text-based" description. However, where geometry is recorded, these units generally behave like other 3D spatial units, such as polygon slices. The decision to include geometry data is jurisdiction-specific and can be applied to any type of spatial unit, allowing for flexibility in how these units are represented.

- **Balance spatial unit:** These represent the remaining volume of a 2D spatial unit after certain 3D volumes have been removed or excised. These remaining areas, or inner 3D regions, can vary in complexity. There are two main variants of how this spatial construct is understood:
  - Primary Interest: The balance unit may be created when a specific volume is excised from the 2D spatial unit to prevent overlap, often due to the creation of a new primary interest.
  - Secondary Interest: The balance unit may define a secondary interest (such as a lease), where overlapping spatial units are allowed, but the original 2D spatial unit remains as a standard base unit.

This concept is particularly useful for managing complex layering and division of space in 3D LAS. In cases where 3D spatial units are modelled as collections of 3D geometries (such as polyhedra) within a 2D surface parcel, the "Balance spatial unit" is the residual unit formed when the 3D polyhedra are subtracted from the larger 2D prism. If the entire 3D domain is represented as a space partition using a 3D topology structure, the Balance unit will resemble a prism on the outside, with cavities or voids created by the internal 3D geometries. This categorisation aids in determining the complexity of spatial units.

The first two categories in the taxonomy—semi-open spatial units and polygonal slice spatial units—share similarities in terms of how data are stored, but differ significantly when it comes to their visualisation and management. Both categories can have subcategories that depend on how their surfaces are defined. These surface definitions can be either:

- Above/below an elevation: In this case, the surface is defined by a horizontal flat plane at a specific height relative to a datum, such as sea level or ground elevation.
- Above/below a surface parallel to the local ground surface: Here, the surface is parallel to the local terrain but offset by a defined distance above or below it, creating a relationship with the topography.

"Multi-valued stepped spatial units," "General 3D spatial units," and "Balance spatial units" represent classes that require more complex methods of storage and visualisation compared to the other spatial unit categories. These units make up a relatively small proportion of spatial units in the real world, so while it is essential to account for and model them, their storage and maintenance processes do not need the same level of optimisation as more common types, such as polygonal slice or semi-open spatial units.

The three classification aspects—real-world spatial unit type, geometric representation, and encoding level—are theoretically orthogonal, meaning that each can vary independently. However, in practice, these aspects are closely interrelated, particularly when managing more complex spatial units, which require more sophisticated handling for accurate representation and data management. Figure 5.5 illustrates use cases of the different types of spatial units' categories, as described above.

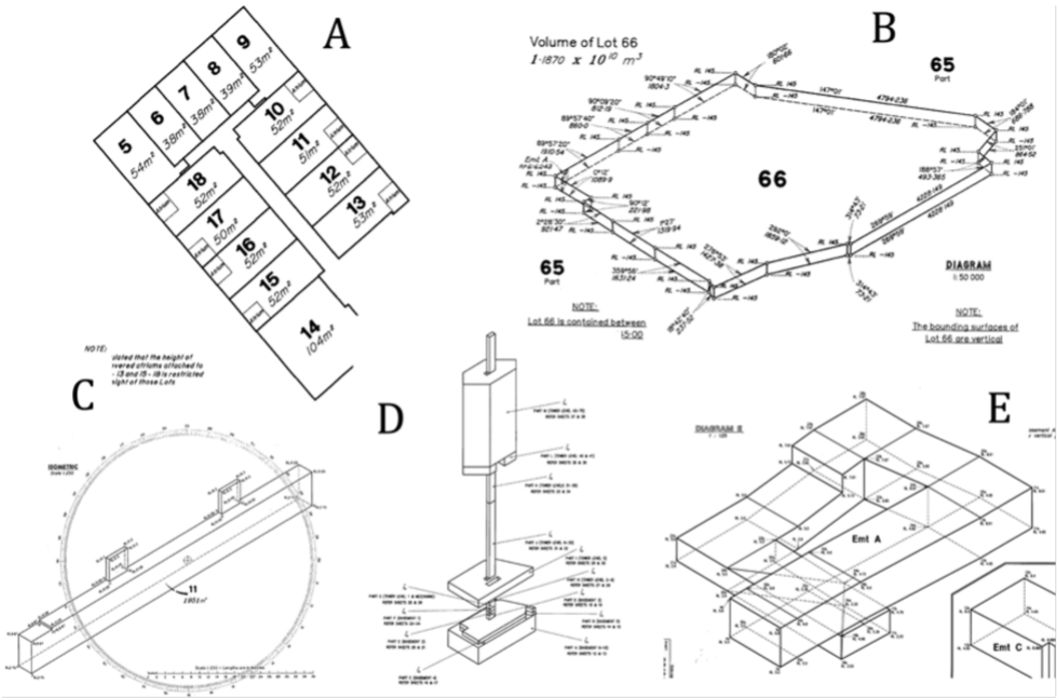

FIG. 5.5 Subcategories of spatial unit geometries: A. Building Format spatial units; B. Simple Slice; C. Single-valued stepped spatial unit; D. Multi-valued stepped slice; E. General 3D spatial unit.

5.3 Sources from design: BIM Legal

The shift towards more integrated, efficient, and sustainable LA practices is increasingly dependent on the reuse of information from the design phase, especially for the general boundary principle. ISO 19152 LADM plays a critical role in this transformation by offering a standardised framework that supports the modelling and management of 3D property RRRs. In this evolving landscape, various design sources can be leveraged as inputs for 3D LA, with a particular focus on the semantics that are relevant to surveyors and other stakeholders involved in LA processes. These design sources include simple CAD drawings, stacks of floor plans, OGC LandInfra datasets, and BIM/IFC files, each offering varying levels of detail and structure that can be adapted to meet the specific requirements of LA systems.

For example, an OGC LandInfra dataset of the Land Division package, can be highly valuable for LA, for development projects. It contains information about boundaries that delimit land ownership, providing the context for fieldwork with measurements and boundary marking. The *LandDivision* component of the LandInfra standard is crucial for linking data on ownership rights (as specified by a *PropertyUnit* class in LandInfra) in land, buildings and other built assets attached to it (OGC, 2016).

LandInfra datasets can also represent legal property units that are not directly tied to the Earth's surface. This is particularly useful for multi-dimensional property rights, such as condominiums. The *Condominium* class in LandInfra defines properties divided into private and common areas under a *condominiumScheme*, representing shared ownership. This semantic structure makes LandInfra a potential source of valuable information for 3D LAS.

Another key concept is *superficieObject*, which covers ownership or other rights over units not bound to the surface, such as underground structures or air rights. These rights are managed through an *encumbranceScheme* class. By incorporating these elements, LandInfra enables a more comprehensive 3D representation of land ownership, helping stakeholders manage complex property structures in LA.

BIM can serve as a valuable data source for implementing 3D LAS, but its reliability depends on data quality, accuracy, and adherence to standards. IFC models provide structured and detailed information that supports the digital registration of 3D legal spaces, enhancing spatial accuracy and functionality. However, inconsistencies in BIM data, variations in modelling practices, and differences in legal requirements may necessitate additional validation and adjustments for seamless integration into

LAS. By incorporating legal space details—such as property boundaries, ownership rights, and restrictions—into building models, BIM can support that spatial descriptions are clear, well-defined, and legally consistent. This alignment enhances the accuracy of land records, ensuring they accurately reflect both the physical reality of buildings and their legal status (Alattas et al., 2021).

This combination of the two international standards (LandInfra and BIM) aims to enhance the management of land and properties by combining detailed building information with LA. In this scene, numerous research initiatives have explored the concept of BIM-based 3D LA registration. A challenge lies in aligning the diverse needs and requirements of various domains—technical, legal, and economic—to create a workflow that is both practical and widely applicable. Beyond the technical aspects, such as modelling and validation, a "BIM Legal solution" must comply with legal regulations to ensure the responsibility, reliability, and accountability of the digitally derived data (Stoter et al., 2024). Additionally, the solution must be economically viable for all stakeholders involved.

Research carried out in this domain, including the recent developments in the standardisation of the second edition of LADM and hence, refer to LA with a wider scope (as presented in section 4.2), is based on the following aspects:

- LADM Part 2: Land Registration – BIM as input in the design source of the spatial unit. Focus is given on the registration of ownership rights in buildings, while exploring rights and restrictions in underground utilities
- LADM Part 4: Valuation Information – BIM as input for valuation and taxation purposes
- LADM Part 5: Spatial Plan Information – BIM as input in the spatial planning process and/ or output.

Aligning legal space details with physical models, such as those provided by BIM, supports digital transformation efforts within the land administration sector. It enables the creation of comprehensive digital records that can serve multiple functions, from land management and urban planning to property transactions and asset management. This integration not only enhances the reliability of cadastral data but also aids in the broader goal of creating more efficient and transparent processes for managing land and the built environment.

Table 5.1 provides an overview of key studies and projects exploring the application of BIM for 3D LA, showcasing a range of methodologies. The studies are categorised into different stages, progressing from generic frameworks and conceptual models to process definitions and prototype implementations.

TABLE 5.1 Representative studies and projects exploring the use of BIM/ IFC for LA

Key Contribution in reusing LADM for 3D LA	Study stage	Authors
• indication of the necessity to incorporate multiple entity types into IFC based on processed surveying measurements to manage indoor cadastral information.	Theoretical framework	Clemen & Gründig, 2006
• introduction of the Unified Building Model (UBM), aimed at enriching BIM-based data models with information related to 3D rights RRRs. • the UBM is further expanded to incorporate four types of legal boundaries necessary for the Swedish jurisdiction, allowing for the accurate depiction of ownership spaces.	Conceptual model	El-Mekawy et al., 2015
• development of scan-to-BIM models for 3D underground cadastral map creation.	Generic framework and use case application	Kim et al., 2015
• emphasis on the need to introduce cadastral requirements in the early stage of the building design • use of space and zone concepts in IFC (IfcSpace and IfcZone respectively) to arrange spaces as legal/ ownership zones for adjacent or disconnected parts. • introduction of topological relationships to extract topological information from a database and automatically generate an overview of legal spaces.	IDM workflow for cadastral registration using BIM	Oldfield et al., 2017; 2018
• extension of IFC to manage legal information of complex, high-rise buildings and 3D legal boundaries and ownership arrangements in Victoria, Australia.	Prototype implementation	Atazadeh et al., 2017a; 2017b; 2017c
• investigation of the use of BIM data for 3D property formation to establish a new working process.	Workflow example & use case application	Andrée et al., 2018
• identification of user needs in IDM and introduction of a BIM-based workflow for LA processes.	Process model in IDM	Sladić et al., 2018; Sladić et al., 2020
• introduction of a complete data processing chain for registering new apartment rights in 3D in the Netherlands. • enrichment of IFC with property unit information by designing a user defined property set with cadastral information, called 'Cadastral Information user defined property set'.	Proof of Concept of a data processing chain	Meulmeester, 2019
• enrichment of IFC by adding Property Sets support building subdivision workflows in Victoria, Australia.	BIM-based subdivision workflow	Olfat, et al., 2019
• introduction of a BIM-based approach for 3D property formation process from organizational, legal and technical aspects using IDM.	Prototype implementation	Sun, et al, 2019
• development of a web-based prototype that enables the representation of 3D legal spaces using BIM. • user requirements' investigation.	Web-based 3D cadastre prototype implementation & usability test	Cemellini et al., 2020
• incorporating survey data into BIM models. • mapping of LADM with IFC.	Enriched IFC with survey data & demonstration in BIM viewers	Atazadeh et al., 2021a; 2021b
• introducing the requirements for spatial analysis in 3D LA and providing a framework for spatial analysis • development of an IFC-based database supporting 3D querying for 3D LA and identification of legal spaces' boundaries	Generic framework, requirements' analysis and use case application	Barzegar et al., 2021a; 2021b

>>>

TABLE 5.1 Representative studies and projects exploring the use of BIM/ IFC for LA

Key Contribution in reusing LADM for 3D LA	Study stage	Authors
• introduction of spatial representation of easements using LADM and BIM by enriching IFC with 3D legal attributes.	Conceptual model and use case application	Ying et al., 2021
• introducing an IFC extension by adding a new entity for representing the legal spaces in the complex buildings.	Conceptual model and use case application	Petronijević et al., 2021
• enrichment of IFC with new property sets that cover ownership and access rights to support indoor positioning and navigation. • development of LADM country profile for Saudi Arabia enriched with several building elements such as the wall, column, and slab. • Three types of rights identified in buildings: private, common/ shared and exclusive common	Conceptual model, LADM-based country profile development and use case application	Alattas et al., 2020; 2021
• introducing a BIM-based solution for LA based on LADM in combination with crowdsourced data.	Prototype implementation using ArcGIS Online	Gkeli et al., 2021
• converting BIM to CityGML, enriched with cadastral information, to provide a 3D database that supports querying for Morocco.	Prototype implementation	Hajji et al., 2021
• assessment of BIM/IFC-models against specific criteria and investigation of the technical issues that still need to be addressed. • development of validation webservice and workflow for IFC models to be used for 3D LA.	IFC validation using FME and use case application	Broekhuizen et al., 2021; 2025
• calculating property valuations based on BIMs in Turkey within the context of condominium ownership.	Use case application	Simsek et al., 2021
• enriching IFC with cadastral information based on the requirements for building subdivision in Iran.	Desktop-based prototype implementation and experts' evaluation	Einali et al., 2022
• integrating LADM and IFC for 3D depiction of condominium rights in Turkey.	Conceptual model based on LADM country profile and use case application	Guler et al., 2022a; 2022b
• automatic definition of three different types of legal boundaries and grouping of the common and private properties within a building based on BIM.	Workflow for boundary definition	Xie et al., 2022
• mapping of IFC and LADM and enriching IFC with property sets for ownership spaces for condominiums in China.	Conceptual model and use cases application	Liu et al., 2023
• introduction of a standardised workflow based on LADM and IFC including legal, organisational and technical aspects of modelling the legal spaces of underground objects.	Legal, organisational and technical workflow based on LADM & IFC and prototype application	Ramlakhan et al., 2023
• Incorporation of IFC elements into the LADM Sarawak country profile.	Conceptual model	Zamzuri et al., 2024
• Investigation of data requirements for a BIM Legal model to support the 3D cadastral registration of apartment complexes that aligns with BIM creation processes in practice.	Pilot preparation	Stoter et al., 2024
• Development of a 3D LAS prototype based on LADM for analysing and visualising RRRs in complex buildings (Figure 5.6).	Web-based prototype implementation and use case application	Mao, 2024; Mao et al., 2024

>>>

TABLE 5.1 Representative studies and projects exploring the use of BIM/ IFC for LA

Key Contribution in reusing LADM for 3D LA	Study stage	Authors
• Development of a 3D web-based representation of legal information of new buildings based on BIM for land registration, aiming to make sales process more efficient (initial 'BIM Legal' project of Netherlands Kadaster)[26].	Web-based prototype implementation and use case application	OGDB[27]
• Investigation of the data requirements for a BIM Legal model that supports the 3D cadastral registration of apartment complexes by the Netherlands Kadaster.	IDS development, conceptual definition and use case application	Roes et al., 2023; Stoter et al., 2024

The studies presented in Table 5.1 address a variety of property types, including apartment buildings, underground assets and indoor spaces and have conducted across multiple countries, including Sweden, Australia, the Netherlands, Serbia, Saudi Arabia, China, Morocco, Turkey and others. In parallel, practical projects focus on reusing IFC for 3D LA, with the Netherlands leading efforts, particularly in response to the pressing demand for thousands of new homes.

These studies also address challenges related to interoperability, standards, and the integration of BIM with existing LA models, showcasing the diverse applications of BIM/IFC in this context. Such efforts contribute to a growing body of knowledge aimed at leveraging BIM for more efficient and accurate 3D representations of land and property-related information (Kitsakis et al., 2022).

Figure 5.6 presents a web-based visualisation of property information at a multi-owner apartment and the respective LADM-based instance level diagram (Mao, 2024)

Therefore, transitioning from traditional methods to BIM-based 3D LA requires continuous ongoing exploration and aligning all parties towards common objectives.

26 It is noted that the author collaborated with Future Insight, a Dutch company known for its innovative cloud-based applications in geospatial and civil engineering project management, the last 2 years of this dissertation. One of the projects being involved is the 'BIM Legal', a joint initiative with partners including the Netherlands Kadaster, Future Insight, BPD, Westport Notarissen, Hermans & Schuttevaer Notarissen, and Dura Vermeer. A key outcome of the project was the creation and distribution of 3D legal information derived from BIM files for real estate use, through a web-based solution tested on new residential projects in the Haag – Landgoed Hoevesteijn development.

27 https://bpd2.ogdb.nl/bpd/project/9531/landgoed-hoevesteijn

FIG. 5.6 Visualisation of property information at a multi-owner apartment and the respective LADM-based instance level diagram (Mao, 2024)

5.4 Sources from data acquisition and survey encodings' requirements

Surveyors capture the physical world through precise measurements and observations, which are then transferred into the digital realm to create accurate representations of land, boundaries, and structures. This transformation from the physical to the digital world requires the use of technical encodings that can efficiently store, manage, and exchange this vital information, supporting practical interoperability.

Acquisition techniques along with various other factors, such as the intended purpose of the data, play a crucial role in shaping the nature of the dataset, also including the integration of crowdsourcing methods. The choice of data acquisition method—whether it will be GPS, LiDAR, photogrammetry, or satellite imagery—determines the level of detail, accuracy, and dimensions captured, while the specific goals of the project dictate the data's structure, format, and required precision.

Semantic interoperability is covered by the LADM Spatial Unit Package and the Spatial Representation and Survey sub-package. However, the encodings to be used must ensure that the collected data can be reliably processed, interpreted, and shared across platforms, enabling seamless integration, consistency, and accuracy throughout the stages of analysis, design, registration, and governance.

The last years, crowdsourcing for cadastral surveying provides a flexible and cost-effective approach to data collection, often used to complement traditional methods. However, it can also serve as a standalone data acquisition method, particularly in regions where the registration of (informal) rights is limited. This approach allows for broader community involvement, enabling the collection of vital land information in areas where formal surveying resources or infrastructure may be scarce, while still supporting the accuracy and reliability needed for cadastral records.

The international survey industry has introduced several encodings and formats (namely AutoCAD dxf/ dwg, OGC LandInfra/ InfraGML, ESRI shp, OGC Geopackage) designed to support the modelling, storage, and exchange of cadastral survey information (Kalogianni et al., 2022b). These formats exhibit both similarities and differences in terms of various characteristics, such as the number and level of detail of attributes they support, the handling of topology/geometry, 3D topology/ geometry capabilities, vendor dependencies, interoperability support, and simplicity. Additionally, collaborative workflows and environments have been developed to streamline the surveying process across its various stages (e.g., on-site data collection, office work, and registration), which is crucial for the efficient and accurate completion and exchange of survey data.

Some of these encodings have been developed or adopted through standardisation organisations, while others have gained prominence due to their widespread use by surveyors and LA authorities globally (see chapter 3). However, many workflows followed within organisation remain vendor-locked, depending on the proprietary platforms developed by specific providers. This highlights the need for standardised encodings tailored to the evolving demands of the surveying industry—especially in cadastral registration—to improve data quality, interoperability, and overall productivity.

A standardised survey encoding intended for use in the LA registration process (based on the LADM survey model, see section 6.3) should meet several key requirements for broad adoption and effectiveness across the industry and the users, as presented in Table 5.2.

Not all requirements are intended to apply universally across every project. Their relevance depends on the project’s defined scope, the available technical infrastructure, and the particular objectives and needs of its users.

TABLE 5.2 Requirements for cadastral survey encodings

Requirements	Description
Industry support and vendor neutrality	**1.** ongoing industry support from survey equipment manufacturers, software providers, and GIS, BIM, and DBMS vendors, supporting compatibility across different system versions throughout the entire encoding lifecycle, **2.** primary users shall be from AECOO and GIS domains, **3.** vendor neutrality, ensuring that the encoding does not depend on specific proprietary systems, **4.** support by various ETL (Extract, Transform, Load) tools to facilitate interoperability with other encodings, **5.** regulatory mandates, particularly from national LA authorities, may impose certain obligations on encodings' use, **6.** compliance with applicable regulations in different jurisdictions.
User familiarity and simplicity	**1.** ease of use is important for field surveyors or other users who are familiar with certain encodings, **2.** familiarity with the encoding.
Technical and performance considerations	**1.** open and scalable format, **2.** web-friendliness is critical, enabling efficient transport via web services and fast, efficient parsing for smooth integration into digital workflows, **3.** automatic conversion from the conceptual LADM survey model, along with rich semantic capabilities and thematic attribute support, is crucial for accuracy and consistency, **4.** support of code lists and enumerations, **5.** human-readable format (preferably in ASCII rather than binary).
Support of 3D and surveying-related data	**1.** support for 2D and 3D geometry, **2.** support for 2D and 3D topology, **3.** georeferencing, **4.** support for coordinate reference systems, **5.** metadata, **6.** support of cadastral features/ thematic attributes, **7.** cadastral source.
Semantic richness	**1.** Automatic conversion from conceptual models, **2.** Support seamless data exchange between field, office, and registration.

5.5 Discussion

This chapter underscores the exponential growth and value of geospatial information across the Spatial Development Lifecycle (SDL) and particularly its growing significance in 3D LA. Different disciplines within the SDL employ unique methods and applications for geospatial data, but fragmentation and data silos often limit efficient information sharing. Challenges such as data loss, inconsistencies, independent methodologies, software dependencies, data redundancies, and a lack of collaboration between key stakeholders further exacerbate these silos. Consequently, data is rarely reused effectively, negatively affecting both the quality and consistency of spatial information.

The chapter addresses these challenges by delving into the integration of cutting-edge digital technologies, such as BIM, GIS, and data acquisition methods, into the SDL to improve interoperability and circularity, facilitating data reuse across all lifecycle stages. The SDL stages, from planning and surveying to maintenance and decommissioning, could benefit from a cross-sectoral approach that supports seamless data collection, maintenance, and reuse. This approach is particularly important for 3D LA applications, as it emphasises the reuse and repurposing of data across all phases of the SDL.

In LAS, spatial units range from common 2D spaces to complex 3D configurations, each varying in complexity depending on data availability, regulatory frameworks, and market demands. Answering **Sub-RQ3a “What are the main types of 3D spatial units based on the complexity of their geometry?”**, this chapter categorises 3D spatial units based on their geometric and legal complexity, aiming to improve management and visualisation within LAS and support more legal clarity across jurisdictions (see also sub-section 5.2).

In this context, spatial unit data sources are fundamental for enabling data reuse, with two primary sources examined in this chapter: data from surveying and data from design. Key data acquisition technologies, including UAVs, GNSS, and LiDAR, provide highly accurate spatial data that support 3D modelling of spatial units, enhance comprehension of legal spaces, and promote transparent decision-making in urban data governance, particularly within LA. Effective data encoding for storage and exchange is vital, especially for LA applications, requiring support of advanced 3D capabilities, integration with existing workflows, and high interoperability across platforms and organizations.

Reusing design-phase data streamlines property registration, planning permission, and other regulatory processes. Studies and projects worldwide demonstrate BIM's integration with LA models, particularly with LADM, highlighting BIM's role in enhancing accuracy and functionality in 3D LA.

The initial 'BIM-Legal' project of the Netherlands Kadaster (introduced in section 5.3) underscores the top-down and bottom-up need to modernise existing LA practices for apartment registration in the Netherlands. Following this pilot, a tender was released to establish a BIM Legal system for the Netherlands Kadaster, aimed at developing a system capable of generating a BIM Legal file—an IFC file enriched with LA-related data. This system is designed to enable users to open, group, edit, and maintain LA-related annotations on BIM objects, as well as to assign cadastral apartment index numbers to specific units. One of the objectives is to enable notaries to make necessary adjustments (i.e. split/ merge spatial units) within the enriched BIM Legal file, which will undergo validation (based on IDS provided by the Dutch Land Registry). Upon successful validation, the system will produce 2D division floor plans.

As part of the discussion, the following **considerations** for using BIM in LA are addressed:

- **Legal aspects:** Current national legislation often lacks provisions for integrating BIM, especially in relation to 3D legal spaces.

- **Data ownership:** The ownership and Intellectual Property Rights (IPR) associated with BIM models are essential for using design phase information. Clear definitions of data rights and usage permissions are necessary, and existing IP regulations should be upheld to protect creators.

- **Data sharing and institutional aspects:** Defining access rights for various groups within LA is critical, as some information must be restricted to protect security and privacy. Embracing BIM as a viable, supplementary communication tool within LA, along with other technological tools, can enhance how stakeholders collaborate and share data, paving the way for more efficient, transparent and integrated LA processes.

- **Data accuracy:** LA relies on precise spatial data and any inaccuracies in BIM models (including also the differences between as-designed and as-built models) can affect land registration and may lead to legal disputes. Ensuring data accuracy, completeness, and correctness is therefore essential before integrating BIM data into LA and therefore, validation services are needed.

- **Standardisation:** Standardisation: To ensure that data can be easily shared and reused, it shall be prepared appropriately in advance. Standardised tools, such as the IDS containing the specifications and minimum requirements that a BIM model must meet, become essential. Standardisation shall be in two levels, conceptual and technical (including encoding). Adopting national or international standards for BIM (i.e. IFC ISO 16739-1:2024), and LAS (i.e. LADM ISO 19152-1:2024 and ISO 19152-2:2025), supports effective data exchange across platforms and enhances interoperability.

6 3D LA Modelling in Support to the Spatial Development Lifecycle

[Sub-RQ3b] **How can 3D spatial units be described in a standardised way?**

[Sub-RQ4b] **Based on the cadastral surveying requirements, how can the survey model for LADM Part 2- Land Registration be developed?**

[Sub-RQ5] **How can a generic, reference LA workflow be designed, built upon the survey model for LADM Part 2- Land Registration??**

This chapter is based on the following publications:
Kalogianni, E., *Dimopoulou, E., Thompson, R.J., Ying, S., van Oosterom, P.J.M. (2020). Development of 3D spatial profiles to support the full lifecycle of 3D objects. Land Use Policy, 98, 104177.*
Kalogianni, E., *Dimopoulou, E., Gruler, H.C., Stubkjær, E., Morales, J., Lemmen, C.H.J., van Oosterom, P.J.M. (2024). Refining the survey model of the LADM ISO 19152–2: Land registration. Land Use Policy, 141, 107125.*

ABSTRACT 3D LA modelling represents a transformative approach to managing dynamic people-to-land relationships, requiring frequent adjustments to spatial units within LASs. These adjustments include subdivision, merging, and re-establishment of boundaries, necessitating precise representation and comprehensive boundary documentation. Given the variability of cadastral survey models across countries, the lack of documentation creates challenges in standardisation, interoperability, and efficiency. As technology and geoinformation systems evolve, cadastral survey methods shall be continuously updated to align with technological advancements, legal frameworks, and societal needs. This chapter addresses these challenges within

the framework of standardisation, ensuring that 3D LA models effectively support dynamic and adaptable LASs.

The chapter begins with the description of the 3D LA modelling approach (section 6.1) that has been followed. Section 6.2 presents the conceptual models of the spatial profiles for 3D spatial units that have been developed in order to enhance LADM's ability to support lifecycle processes and to improve interoperability across disciplines and project phases, addressing the demand for robust 3D support. Following, section 6.3, presents the conceptual model of the LADM refined survey model that has been developed and incorporates participatory land-rights recordation processes alongside traditional professional data collection methods, reflecting a global trend toward more inclusive approaches in cadastral surveying. A notable addition to this model is the incorporation of the Galileo High-Accuracy Services (HAS), which is anticipated to become a valuable tool for LA applications, providing precise satellite-based corrections to users globally. Finally, section 6.4 introduces a generic cadastral survey workflow that combines administrative and technical aspects, aligned with the LADM survey model and accommodating diverse national contexts. This approach aims to improve the effectiveness and collaboration in documenting land rights.

The chapter concludes with a discussion in section 6.5.

6.1 3D LA modelling approach methodology

In this chapter, Action Design Research (ADR) is used. ADR, proposed by Sein et al. (2011) is a research methodology that combines Design Science Research (DSR) (Hevner et al., 2010) and Action Research to create prescriptive design knowledge (guiding principles for designing artefacts that are both scientifically valid and practically applicable), while actively intervening in a real-world context. This knowledge emerges through iterative cycles of building, testing, and refining the artefact in real-world settings. It aims to develop and evaluate artefacts in an organisational setting to address practical problems. While DSR focuses on studying artefacts within their context, Action Research emphasises intervention in a social situation to both improve it and gain insights. ADR merges these approaches, allowing researchers to develop artefacts while actively engaging with the environment where they will be implemented.

By integrating design and social intervention, ADR ensures that solutions are both theoretically grounded and practically useful, making it an effective methodology for research in technology, business, and LASs.

The development of the models and workflow presented in this chapter represents an in-depth elaboration of the ‘design and development phase’ within the design science research methodology, as outlined in Section 1.2 and depicted in Figure 1.3. Therefore, Figure 6.1 illustrates this detailed 3D LA modelling approach followed in this chapter.

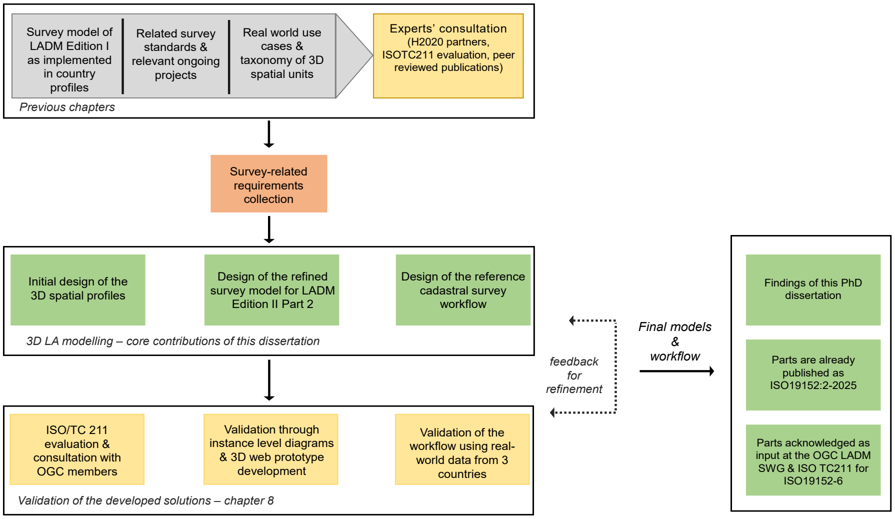

FIG. 6.1 The steps followed for 3D LA modelling activities performed in this chapter

The modelling builds upon a critical analysis of the LADM Edition I survey model, its evolution across various country profiles, and relevant cadastral survey standards and projects, as outlined in the preceding chapters. To address the survey-related requirements (Table 5.2), the developed artefacts (depicted with green colour) comprise the 3D LADM spatial profiles, the LADM survey model, and a reference cadastral survey workflow aligned with LADM. These artefacts were produced through a collaborative and iterative approach that actively engaged domain experts and practitioners. To strengthen their robustness and ensure practical relevance, expert consultation and validation activities were incorporated. Feedback from surveying professionals, including equipment manufacturers, was particularly influential in shaping the integration of Galileo High Accuracy Services and participatory methods within the model. Moreover, members of ISO TC 211 provided critical validation, ensuring the alignment of the outcomes with international standardisation efforts. The validation process and its findings are presented in Chapter 8.

6.2 LADM Edition II – Part 2 spatial profiles

Spatial profiles are essential for effectively represent the different types of 3D spatial units, enhancing the standard's ability to support lifecycle processes and improving interoperability across disciplines and project phases. For any given spatial representation within the LADM, a spatial profile streamlines the required classes and attributes to the essentials.

LADM Edition I provided six spatial profiles, which this dissertation extends with six additional ones. *This research marks the first steps toward the creation of 3D spatial profiles, highlighting their necessity for modern LASs.* The profiles developed in the context of this research, support complex configurations, such as 3D structures combining 2D and 3D elements, while allowing country-specific implementations to select and combine profiles as required. Their development responds to the increasing demand for robust 3D support in LA, evidenced by multiple LADM-based profiles, prototypes, and pilots (FIG 2018a, FIG 2018b), and ensures alignment with other standards for representing the built environment, including BIM/IFC, LandXML, and LandInfra.

The six new profiles, structured according to the revised taxonomy in sub-section 5.2.2, are deliberately kept simple. They form the basis for ongoing discussions that led to their inclusion in Annex C of ISO 19152-2:2025a, while recognising that further development is still required. These profiles are the following:

- "Simple" 3D profile
- 3D "General Boundary" profile
- 3D "General Spatial Unit" profile
- 3D Spatial profile for "single-valued stepped spatial units"
- 3D Spatial profile for "multi-valued stepped spatial units"
- 3D Spatial profile for "balanced spatial units"

Figure 6.2 presents the spatial profile for the *“simple” 3D spatial units*: polygonal slice and semi-open spatial units. At the class Simple 3D_SpatialUnit, which is a specialisation of LA_SpatialUnit, the value of dimension attribute is fixed to “3D”. Moreover, two attributes are added: upper_surface and lower_surface defining the horizontal bounded surfaces. A constraint that the upper_surface shall have a higher numerical value than the lower_surface is imposed to prevent the two surfaces to intersect and to manage appropriate storage, while two attributes for the minimum and maximum Z are added.

An important aspect is that one of the surfaces may be the earth surface. For that reason, it is modelled as "blueprint" for an external class and is related to relative z/height/depth types of representations and/or to support in 3D parcel dissemination. Finally, the attribute surfaceRelation indicates if 3D Parcel is above, below or crossing earth surface. At the Simple3D_Level class value of the attribute structure is fixed to "polygon".

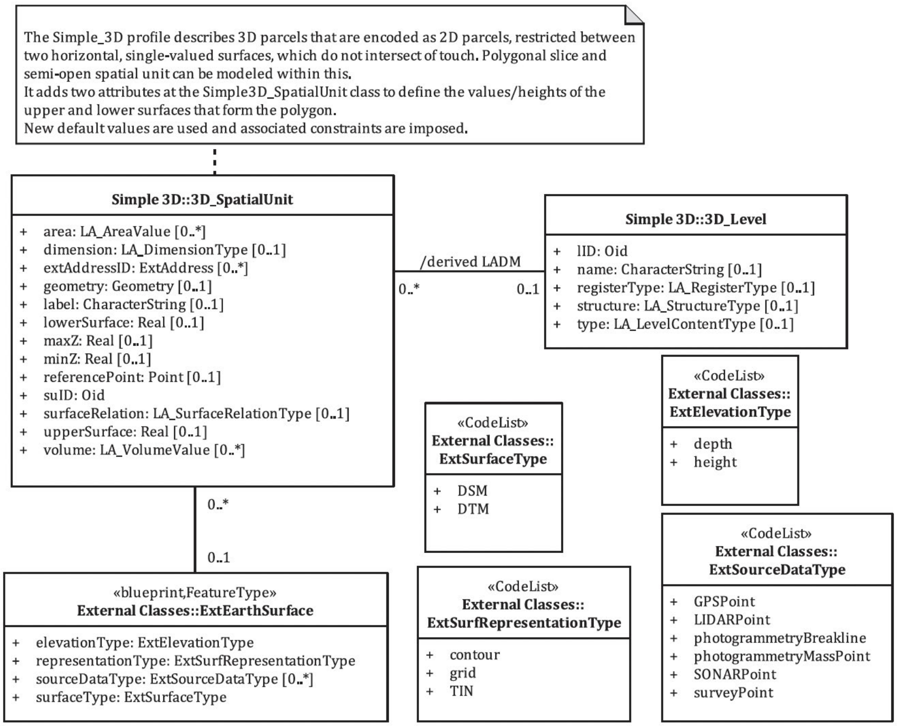

FIG. 6.2 Conceptual model of the "Simple 3D" Spatial Profile

In the case of a building or construction type of spatial unit, where the spatial unit is legally defined by the boundaries of an existing or planned structure, there are two ways to describe and spatially represent the spatial unit: by referring to a building format or by defining its actual shape using geometrical types. The actual geometric form of building/construction type of spatial units can vary, mainly being polygonal slices, but all categories are possible.

Thus, in the *"3D general boundary" profile* both options are included by introducing new, optional attributes. When the building/construction format spatial unit is defined by geometry type of two attributes are added, similar to the profile for “simple” 3D spatial units: upper_surface and lower_surface defining the horizontal bounded surfaces, accompanied by the respective restrictions. At the class GeneralBoundary_SpatialUnit, which is a specialisation of LA_SpatialUnit, the value of dimension attribute is fixed to “3D”, see Figure 6.3. Additionally, a reference to the “ExtPhysicalBuildingUnit” class is added to provide a direct link to a building element.

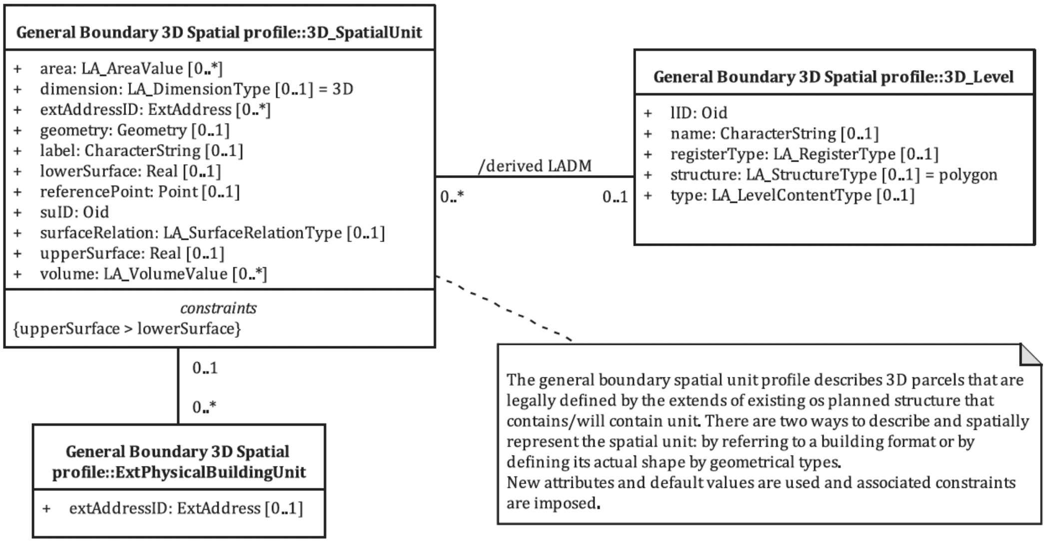

FIG. 6.3 Conceptual model of the “3D General Boundary” Spatial Profile

The *spatial profile for a general 3D spatial unit* aims to cover 3D geometric objects. These are still defined by a footprint polygon, and an upper_elevation and lower_elevation, but in this case the elevations do not define the corresponding upper and lower bounded surfaces; instead, they provide a limitation on the extent for searching and potentially support low LoD representations. In addition, there will be a collection of LA_BoundaryFace objects to define the exact extents of the spatial unit. For the general spatial unit, two simplified spatial profiles are proposed, one in a topological model (Figure 6.4) and the other in a polygonal encoding (Figure 6.5). Those profiles are kept as simple as possible and will be further explored in relation to real-world use cases. A case of general spatial unit is presented in Figure 6.6.

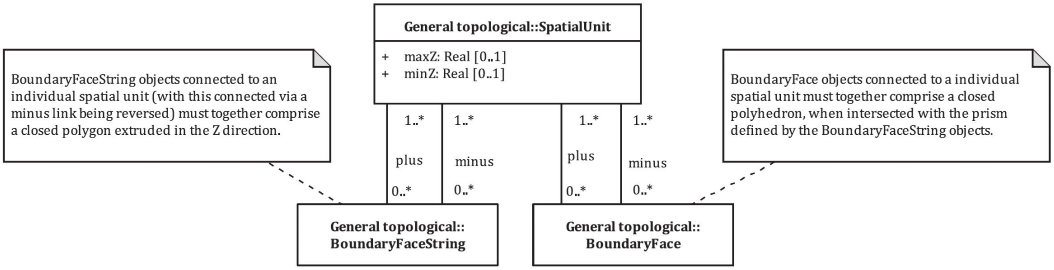

FIG. 6.4 Conceptual model of the “general spatial unit in a topological model” (simplified) spatial profile

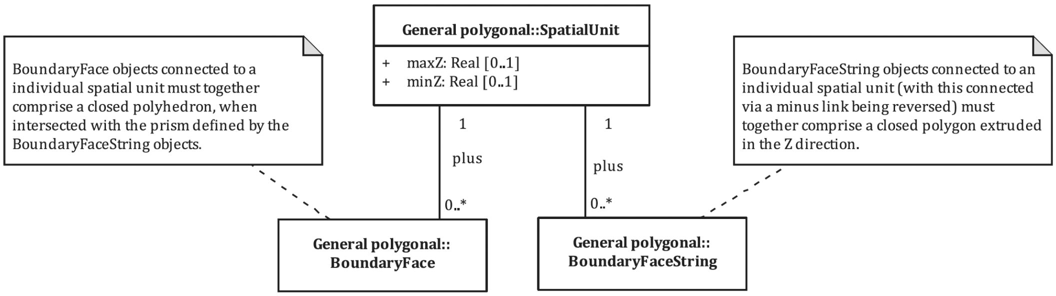

FIG. 6.5 Conceptual model of the “general spatial unit in polygonal encoding” (simplified) spatial profile

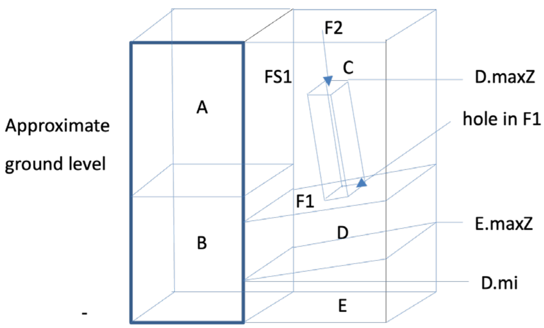

FIG. 6.6 Faces and Face Strings – Showing two simple spatial units A and B, a general spatial unit D (which includes the airshaft to above the surface, and two balance spatial units C and E which are open above and below respectively

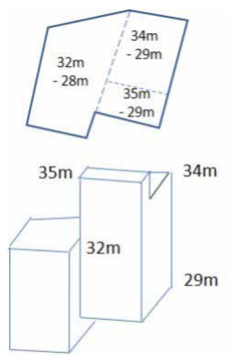

FIG. 6.7 Single-valued stepped spatial unit

TOC

In Figure 6.6, face string FS1 defines the boundary separating A and B from C, D and E. In a topological encoding, it would be stored only once, with a plus link to A and B, and a minus link to C, D and E. Likewise face F1 (which has a hole in it) has a plus link to C, and a minus link to D (as does face F2).

Single-valued stepped spatial units (Figure 6.7) are a special case of a general 3D spatial unit, in terms of the database storage. Modelling this type of spatial unit is simplified – as it is relatively simple to allow the data preparation officer to omit all vertical faces – only needing to encode the footprint polygon and the horizontal faces. The data capture program can then, easily generate the vertical faces. It is noted that the division into upper surface faces and lower surface faces does not need to be imposed in the storage schema, being a simple matter of the orientation of the faces (clockwise from above for the lower faces, anticlockwise from above for the upper faces).

Similar to the single-valued stepped spatial units, the *spatial profile for 3D multi-valued stepped spatial units* is a special case of a general 3D spatial unit. For encoding purposes, it may be useful to consider the face objects to be divided into upper and lower surface definitions.

There are two strategies to model *balance spatial units*: they can be explicitly stored as being the balance of "spatial unit A" when the subunits are excised – thus requiring the accessing software to determine the shape and detailed definition of the object; or the balance spatial unit can be stored in the same form as any general spatial unit (thus modelled implicitly with avoidance of redundancy). It is relatively easy to use a spatial subtraction operation to generate a balance object – taking the enclosing object and subtracting all the enclosed objects.

Therefore, in the context of this dissertstion, it was decided to choose the first approach and model this type of spatial units as the “remainder” between a normal 2D and 3D parcel, as depicted in Figure 6.8. The remainder parcel is not an independent one, and thus its spatial profile depends on the spatial profile of the core/basic 3D parcel. A link between the (‘normal’) 2D parcel and the 3D parcel is created, which is a ‘safer’ way to connect the two parcels, in a sense that it shows an explicit warning that the party does not own the whole 3D column, but a part of it, while there is no dependency on an implicit relationship.

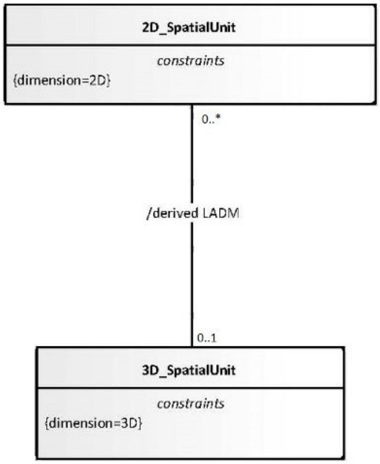

FIG. 6.8 The initial spatial profile for the balanced spatial unit

At a conceptual level this association can be derived, and it is modelled in this way, while at the implementation level it can be decided whether it would be explicitly or implicitly modelled. The profile for this type of spatial unit is initially straightforward; however, depending on how the 2D parcel is implemented, additional constraints may need to be introduced during its further development. For instance, the association can become explicit when the 2D parcel is described by simple text (2D text based spatial profile) or points (2D point based spatial profile).

The categorisation of spatial units in the LADM-based taxonomy incorporates key principles tailored to the representation and management of 3D spatial data. Building on concepts proposed by Thompson et al. (2017), these principles are applied in this dissertation to structure spatial units effectively while accommodating both 2D and 3D configurations. They provide the foundation for the development of the initial six 3D spatial profiles and are listed below:

I "Footprint Polygon"

The concept of a "footprint polygon" serves as the foundational element of a 3D spatial unit. A footprint polygon represents the base area of a spatial unit, restricted by (vertical) faces extending above and below the actual parcel. This concept:

- provides a Simple 2D limitation on the extent of the spatial unit: By defining a 2D outline for the spatial unit, the footprint polygon sets a straightforward boundary;
- links 2D and 3D spatial units;
- enables database indexing: in non-topological storage, it can be stored as a polygon, allowing efficient 2D indexing;
- supports topological structures: for topological structures, the face string network can function as a 2D planar graph;
- facilitates query and update with 2D tools: Vertical boundaries allow compatibility with 2D software, enabling queries and updates within a 2D framework.

II Bounded Surfaces

3D spatial units typically have vertical faces along with an upper and/or lower face, defining the spatial unit's boundary. Two key-aspects can be underlined:

- upper and lower boundaries: Bounded surfaces establish constraints above and below the spatial unit, indirectly indicating its maximum and minimum Z values.
- defined constraints and multiplicity: Each bounded surface comes with constraints, and multiplicity is appropriately defined for the various 3D configurations.

III Absolute or relative height

To describe the spatial unit's position in 3D space, an optional attribute for absolute height is proposed.

- Absolute Height: Provides a fixed, global reference for the unit's position.
- Relative Height: Offers a flexible description, allowing spatial units to be referenced relative to other 3D elements or ground levels, useful for describing 3D parcels.

IV Surface Relation Attribute

The LA_SurfaceRelationType attribute specifies whether the elevation is relative to the ground.

- Upper/Lower Relative Elevation: The attribute indicates if the upper or lower elevations relate to the ground (e.g., “from 20m below to 20m above ground surface”).
- Supports Complex Geometries: This is especially valuable for complex geometries where adjacent 3D units have differing relative Z values, even though achieving topological consistency between adjacent units in such cases may be challenging.

V Reference to a Topographic Object

Spatial profiles can include references to external topographic objects, specifying 3D boundary surfaces linked to external data.

- Association with External Registration: This enables the spatial unit to be linked with externally registered topographic data, enhancing contextual relevance.

VI Reference to Another Surface

In certain cases, spatial units may refer to another surface for their definition—this may be the Earth’s surface or another spatial unit.

- Association to Reference Surfaces: By establishing an association with other surfaces, the model can represent spatial units that are partially or fully based on other spatial structures, enhancing adaptability across different spatial contexts.

6.3 LADM Edition II – Part 2 Survey Model

6.3.1 General

Cadastral surveying plays a critical role in defining property boundaries and documenting easements and restrictions, which form the basis of a LAS. Although fundamental to Cadastres and LASs, surveying processes and models often lack international standardisation, are inconsistently documented, and require frequent updates due to rapid advancements in technology and geoinformation.

Traditionally, cadastral data collection for LA is conducted exclusively by licensed land surveyors, using specialised survey equipment and detailed attribute forms. However, in recent years participatory data collection methods have emerged, where right holders actively participate in data collection under the supervision of surveyors or other land professionals (Morales et al., 2021). This approach is particularly valuable in areas where conventional surveying may be less feasible or cost-effective. However, for participatory methods to be effective, equipment and user interfaces must be simplified, as traditional complex tools are impractical for non-expert users.

The inclusion of participatory data collection poses challenges in adapting data acquisition methods to be both robust and user-friendly. Simplified technology and workflows are necessary to make these tools accessible to the public, while maintaining data accuracy and reliability. Additionally, sophisticated post-processing algorithms are needed to validate and refine the data collected by non-specialists, ensuring that professional standards are met.

In response to evolving needs, the LADM survey model has been undergoing a comprehensive revision since 2019 (Shnaidman et al., 2019). Several enhancements to LADM Edition I have been explored by the author of this dissertation, including the addition of new attributes for the class LA_SpatialSource, the introduction of association classes, and the development of corresponding code lists. These improvements to the Edition I of the standard aim to more effectively capture the complexities of surveying processes and have shaped the outcomes of this research.

Additionally, in the context of the H2020 GISCAD-OV project[28], further investigations were made to enhance the model's interoperability with other standards. This involved examining mature approaches to survey models, with particular attention to the OGC LandInfra Conceptual Model, specifically Part 6 – Survey. The findings from this investigation resulted in refinements to the LADM survey model, ensuring alignment with established international frameworks and addressing current technological needs. As reported by Kalogianni et al. (2021b), the revision process also focused on identifying and integrating key concepts related to data acquisition methodologies and tools. These updates aim to better represent modern surveying practices and align with related standards, ensuring that the model remains robust and relevant.

The final update of the survey model provides a more flexible and inclusive framework for data acquisition. It supports both traditional and participatory approaches while accommodating a wide range of data acquisition techniques, making it adaptable to diverse land administration contexts. The survey model will encourage the application of standardised processes, improving consistency and interoperability across different regions. Additionally, it incorporates technological advancements in data processing and methodology, making it better suited to the tools and techniques of modern land administration.

In this context, in sub-section 6.3.2 the detailed LADM survey model is presented. It is noted that it is one of the core contributions of this dissertation and has been adopted by ISO19152-2:2025 (voted as ISO standard in June 2025).

6.3.2 Conceptual model of the refined LADM Survey Model

To address the need for describing a wide variety of spatial unit types, the categories of legal spaces associated with cadastral objects, as defined in Edition I of LADM (LA_LegalSpaceBuildingUnit and LA_LegalSpaceUtilityNetworkElement), have been further specified. In this regard, two new subclasses have been introduced:

- **LA_LegalSpaceCivilEngineeringElement:** This subclass is designed to represent the legal spaces of infrastructure elements such as bridges, tunnels, and other civil engineering structures. A reference to the physical (technical) description of the civil engineering element, together with its status and type is described.

28 https://giscad-ov.eu

- **LA_LegalSpaceParcel:** This subclass is used to describe the legal spaces of traditional land parcels, along with its land use.

These subclasses allow for a more precise and comprehensive representation of the most used spatial units, accommodating the management of legal spaces associated with both civil engineering infrastructure and traditional land parcels (see Figure 6.9).

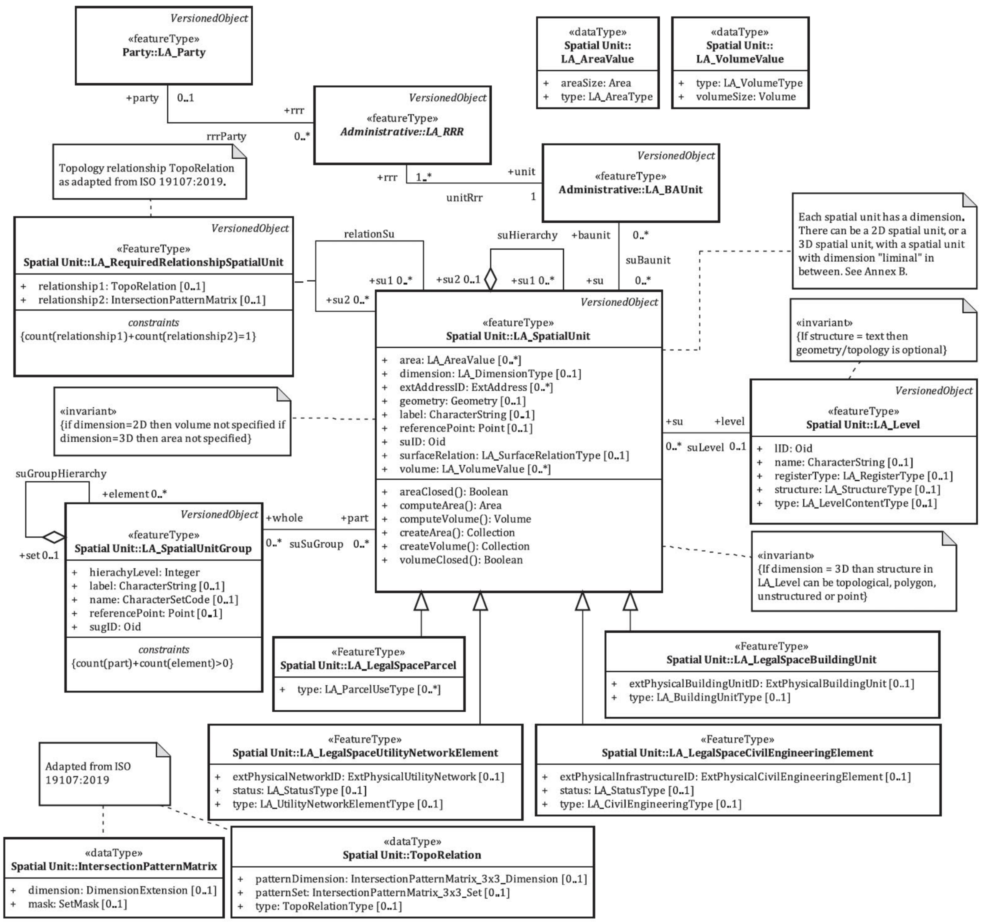

FIG. 6.9 Subclasses of LA_SpatialUnit of the Spatial Unit Package of the LADM survey model, with associations to other basic classes

The concept of a spatial source in the revised LADM standards-series is designed to accommodate both official and informal sources, providing flexibility for different LA contexts. For instance, a spatial source could be a registered survey plan or an aerial photograph, supporting both formal and participatory surveying acquisition methods. Furthermore, paper-based documents, including scanned records, can be considered to be integral components of the land administration system, ensuring inclusivity in data representation.

In the LADM framework, a spatial source can be linked to a survey, which is treated as a specialisation of the OM_Observation class as defined in Observation & Measurements ISO 19156:2023 (ISO, 2023). This framework describes a set of measurements that may be acquired using various survey techniques. The OM_Observation class represents the observation interface, while the OM_Process details the survey procedure used (Figure 6.12). These elements provide a structured approach to integrate observations and processes within the LADM.

In the context of this thesis, the LA_SpatialSource class, as included in Edition I of the standard, has been updated and enriched to accommodate these enhancements. These developments regard updates on existing attributes and addition of new ones, as follows (Figure 6.10 and Figure 6.11):

- **type:** Specifies the type of the source (i.e. aerial image, point cloud, etc.). This attribute existed in Edition I, but its code list values have now been expanded to cover a broader range of source types, specifically related to the technique of the survey used.
- **media:** Indicates the media type associated with the source, such as digital files, sketches, etc.
- **automationLevel:** Describes the level of process automation involved in handling the source, ranging from manual to fully automated processes.
- **surveyPurpose:** Enumerates the individual purposes of the survey, such as boundary delineation, infrastructure mapping, or land use planning, which is crucial in the LA domain.

Figure 6.10 presents part of the surveying and representation sub-package with associations to other basic classes and Figure 6.11 illustrates the code list values of the respective sub-package.

These developments provide a more structured and detailed model for describing spatial sources, enabling better integration and support for diverse surveying processes within the LADM framework.

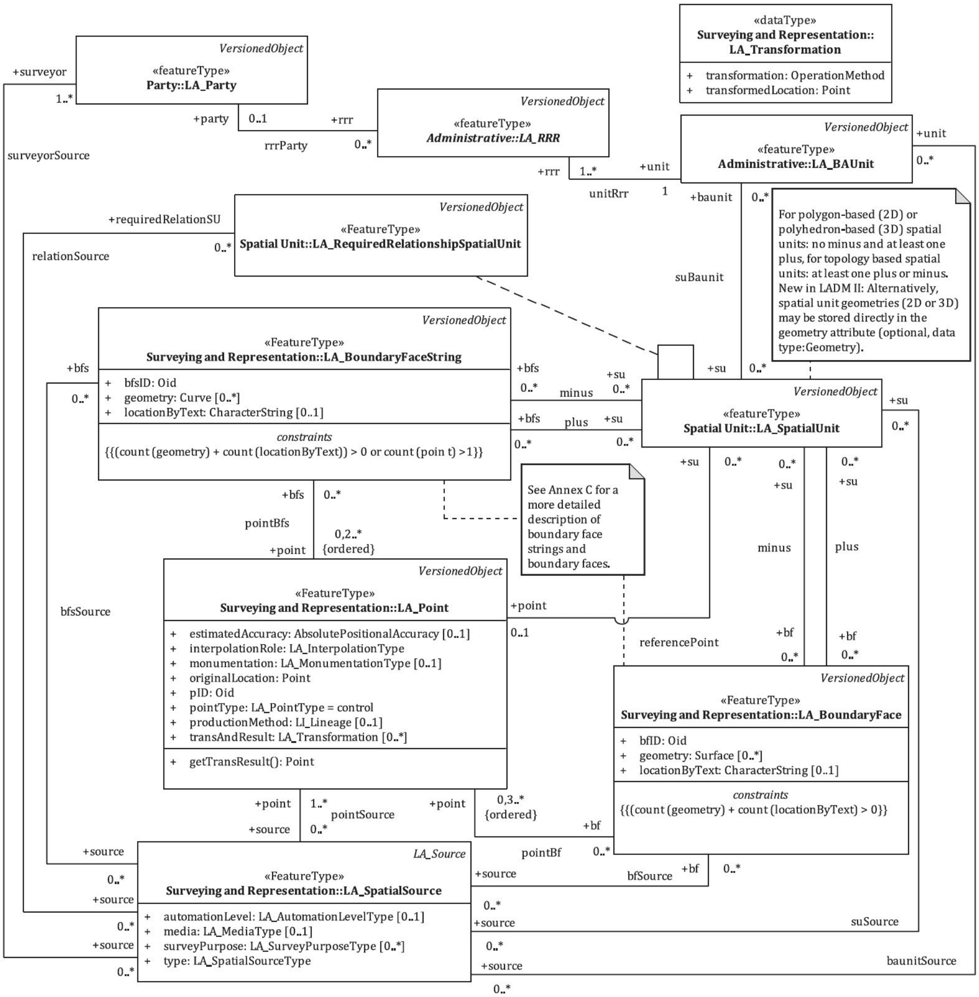

FIG. 6.10 Content of Surveying and Representation sub-package of the LADM survey model, with associations to other basic classes

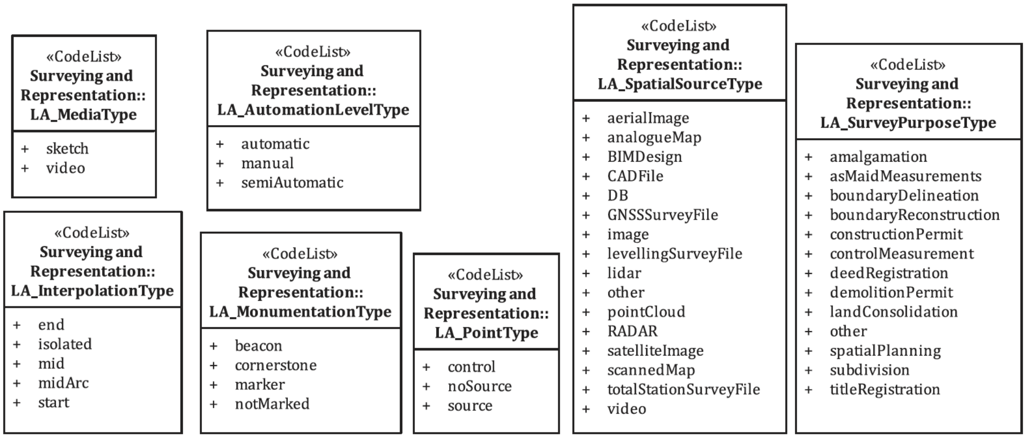

FIG. 6.11 Data types and code lists of Surveying and Representation sub-package of the LADM survey model

In the context of reusing information from other phases of the SDL, the spatial sources of the survey model have been enriched in the context of this dissertation. Specifically, two new subclasses are created to document survey-related information in spatial sources as a set of measurements with point observations, as well as sources from the design phase (i.e. floor plans or 3D models).

It is noted that the attributes of the LA_SpatialSources are not depicted in the following figure to enhance visibility (they have been presented in Figure 6.10). As illustrated in Figure 6.12, the two new subclasses are:

- **LA_DesignSource:** This subclass represents sources generated during the design process for objects to be implemented in reality and enables information reuse.
- **LA_SurveySource:** This subclass handles sources with data collected during actual surveying activities, providing detailed information on measured spatial units. A set of measurements such as distances, bearings, GNNS observations etc. as obtained via various survey techniques and stored on designated media.

Figure 6.14 presents the code lists of the surveying and representation sub-package.

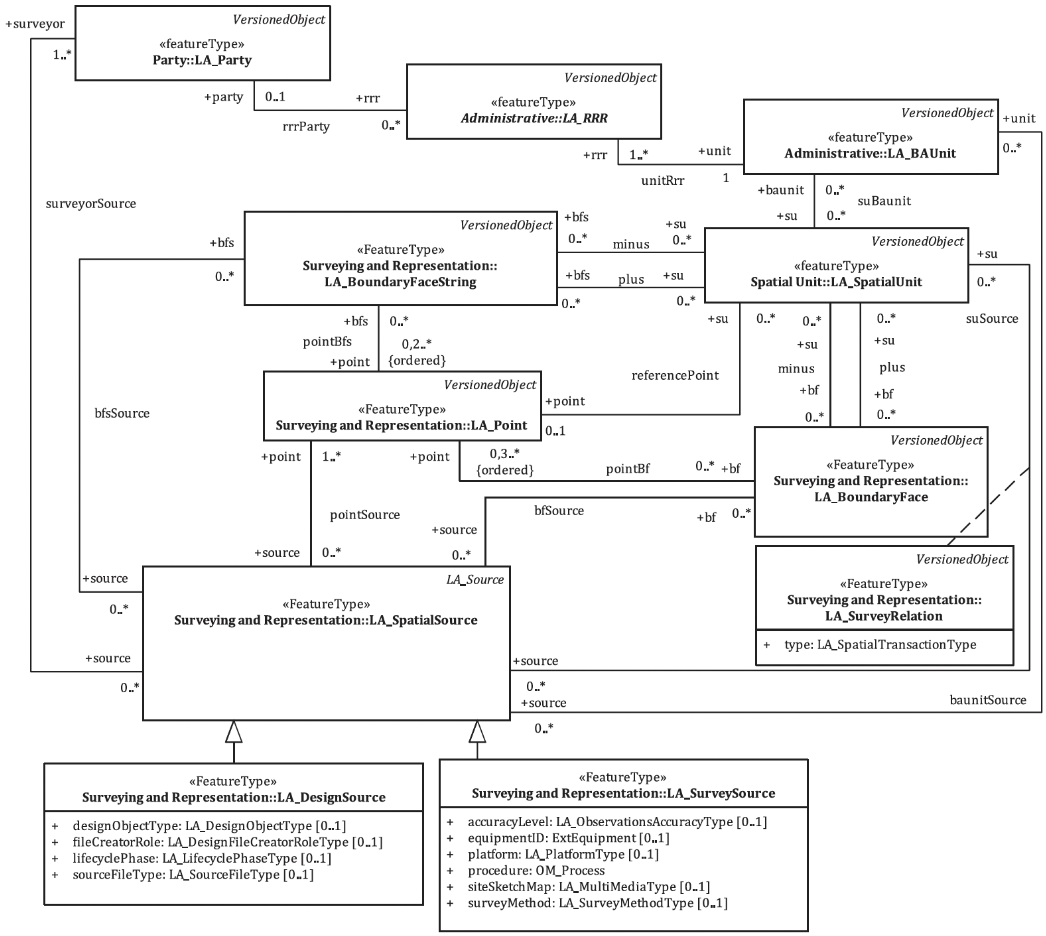

FIG. 6.12 Subclasses of LA_Source of the Spatial Unit Package of the LADM survey model

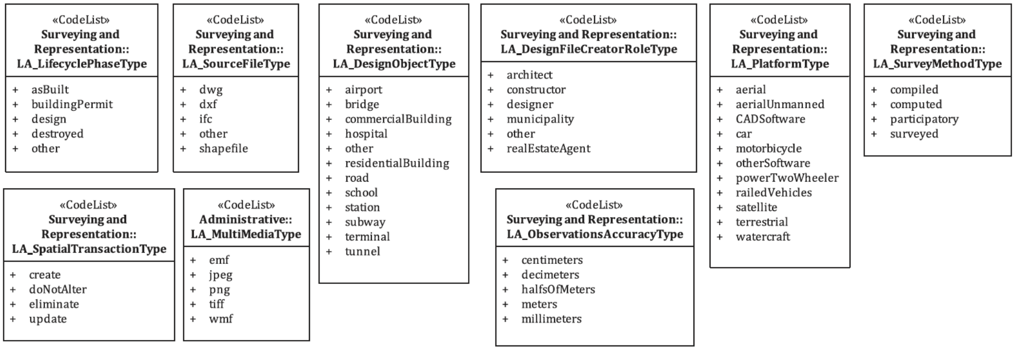

FIG. 6.13 Code lists of the Surveying and representation sub-package of the LADM survey model

The new classes regarding spatial unit types and spatial sources have been integrated into the detailed survey model of ISO 19152-2, reflecting a more comprehensive and adaptable model. Among these developments, the introduction of an association class further strengthens the model's capability to represent relationships and roles in spatial data management processes. Moreover, the association class LA_SurveyRelation establishes a link between LA_SpatialSource and LA_SpatialUnit and is designed to provide deeper insights into the type of spatial transaction occurring, such as the creation, modification, or validation of spatial units based on the associated spatial source. Additionally, the optional association class between LA_Party and LA_SpatialSource captures the varying roles that a surveyor may assume in the context of data acquisition (Figure 6.12).

Coordinates could be captured as vector geometries. These geometries, which may include points, lines, surfaces and volumes, are acquired using various methods. In the field, this can involve classical topographic surveys or satellite navigation systems, while in office settings, input from design or other sources can be reused. Spatial data may also be compiled from diverse sources, such as forms, field sketches, or orthophotos. Additionally, spatial units can be identified through methods such as interpretation of photographs, images (e.g., satellite imagines and orthophotos), or topographic maps. Advanced imaging techniques, which utilise multiple images taken from different angles, can also be employed for this purpose.

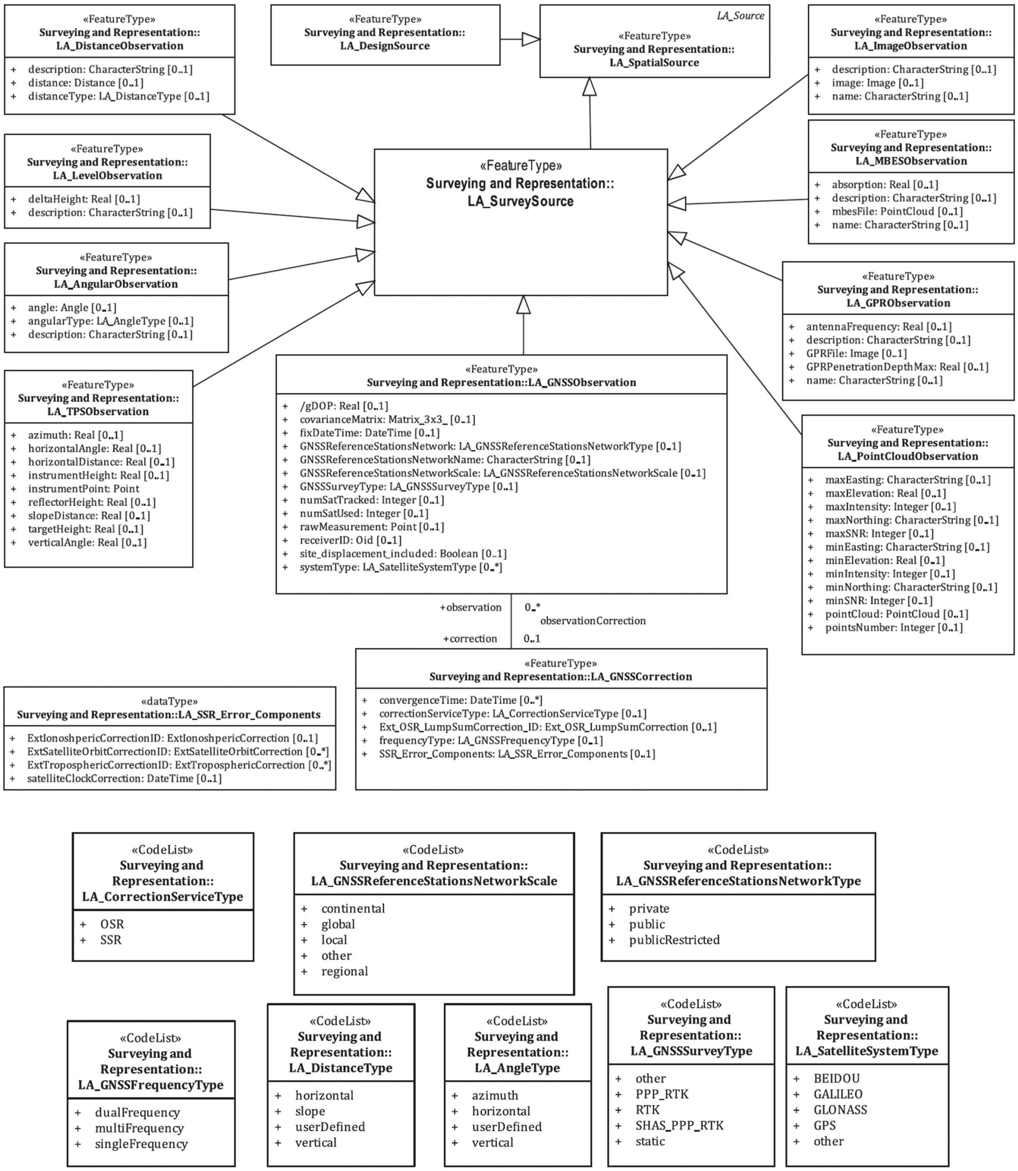

FIG. 6.14 The sub-classes of LA_SurveySource of the Surveying and Representation sub-package of the LADM survey model and the relevant code list values

Both 2D and 3D representations of spatial units are structured using boundary face strings for 2D instances and/ or boundary faces for 3D instances. Individual points are systematically associated with the class LA_SpatialSource. While it is not required that the complete spatial unit is represented, a spatial source may be

TOC

associated to several points. Systems with 2D or 3D representations of spatial units are also capable of integrating multiple reference systems, ensuring compatibility and precision across various datasets. The LADM effectively accommodates such data sources, geometries, and reference systems.

To provide this functionality nine (9) subclasses are added at the LA_SurveySource, representing the different methods for observations' acquisition (Figure 6.14):

- LA_DistanceObservation referring to distance observations,
- LA_LevelObservation concerning height observations,
- LA_AngularObservation referring to angular measurements,
- LA_ImageObservation for image-based observations,
- LA_TPSObservation observations obtained by using total-station,
- LA_PointCloudObservation for point clouds observations obtained by Lidar, dense matched images, and other equipment,
- LA_GNSSObservation obtained by using GNSS receivers,
- LA_GPRObservation obtained by ground penetrating radar and
- LA_MBESObservation obtained by multibeam echosounder.

A new class, GNSSObservation, is introduced to enable the modelling of corrections applied to GNSS measurements, including selected attributes from the High Accuracy Service. This class serves as the repository for all data associated with GNSS correction processes and comprises five attributes, detailed below. While some of these attributes capture raw measurement data, others represent semi-processed observations, which are essential for capturing for cadastral surveying and for the integration within the LADM.

- convergenceTime, where the convergence time of GNSS observation is recorded. A provision is made to register more than one convergence time in case this is needed (for instance when recording Galileo HAS observations);
- frequencyType, where the frequency range of GNSS corrections is stored with predefined values from the code list LA_GNSSFrequencyType;
- correctionServiceType, where the category of the corrections' used is defined, a code list LA_CorrectionServiceType is available here;
- the Ext_OSR_LumpSumCorrection_ID, serves as an external link to the source were the lump sum of corrections of the Observation Space Representation (OSR) is stored and
- the SSR_Error_Components, with the values of the components of corrections of State Space Representation (SSR) can be defined. In order to support the need to define the various SSR components, a new data type has been created: LA_SSR_Error_Components.

OSR and SSR are the two qualities of GNSS corrections, as illustrated in Figure 6.15. These methods address errors that arise in GNSS positioning due to factors affecting the apparent range (pseudo range). The pseudo range is calculated by multiplying the observed travel time of a GNSS signal from a satellite to a receiver by the speed of light. However, the travel time is influenced by multiple error sources, such as satellite orbit and clock errors, biases in satellite and receiver hardware, and in ionospheric and tropospheric. These errors collectively reduce the accuracy of real-time positioning when relying solely on satellite signals.

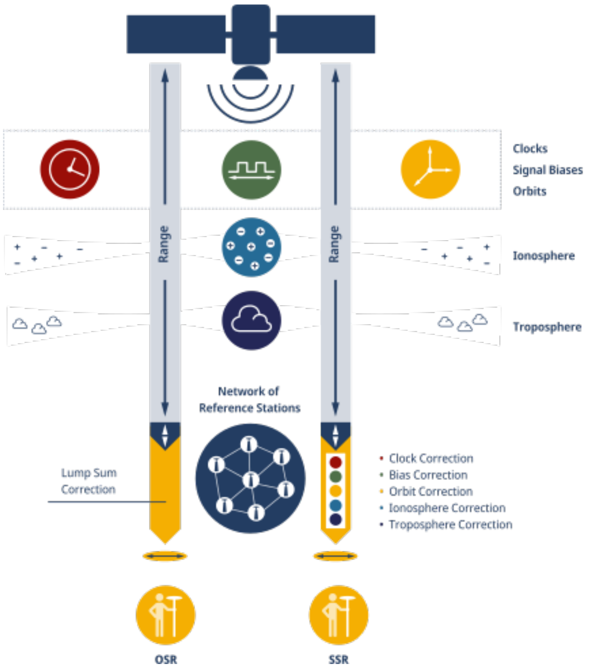

FIG. 6.15 OSR and SSR (https://www.geopp.de/ssr-vs-osr/)

In conventional Real-Time Kinematic (RTK) services, these errors are aggregated and observed by a network of reference stations. The resulting corrections are then transmitted to the rover (mobile receiver) as range corrections, which are specific to each supported combination of satellite, frequency, and signal type. The OSR method requires that all reference stations within the network process same GNSS signals, maintaining a homogeneous network. Furthermore, users must support the same signal configurations to benefit from the provided corrections.

The OSR approach, while effective in real-time applications, imposes strict requirements on the compatibility and homogeneity of the reference network and user equipment. It relies on direct corrections for observed ranges, making it well-suited for applications where precise, real-time positioning is necessary, but dependent on the availability and consistency of the network. OSR corrections are included in the refined LADM survey model at the attribute "Ext_OSR_LumpSumCorrection_ID", which serves as an external link to the source were the lump sum of these corrections is stored.

With the SSR approach, GNSS corrections are generated by a network of reference stations that decorrelate and estimate individual GNSS error components, or "states", which include the following:

- Satellite Clocks: Errors in the satellite's internal clock that affect timing precision.
- Satellite Orbits: Deviations in the actual position of the satellite from its predicted orbit.
- Satellite Signal Biases: Variations in the satellite's transmitted signal caused by hardware discrepancies.
- Ionospheric Delay/Advance: Effects of the Earth's ionosphere on the signal as it propagates.
- Tropospheric Delay: Signal delay caused by atmospheric conditions in the troposphere.

The SSR method utilises this network of reference stations to estimate these error components over a large area and then transmit them to users within the coverage area via the internet and/or satellite communication. Thus, this method enables each GNSS receiver to locally model and apply corrections for these error components to its own observations.

The error components in SSR are structured and modelled in the refined survey model in a new data type called LA_SSR_Error_Components, as depicted in Figure 6.14.

6.4 LADM Edition II – Part 6 A reference cadastral survey workflow

This section presents a generic cadastral survey workflow, as a series of activities aimed at effectively documenting rights in land and their boundaries. These activities encompass both the initial acquisition of data to describe the present status and the efforts required to modify this status during transactions. The documentation primarily refers to spatial units, which are identified by the holders of the rights associated with them. When required, physical markers, such as monuments, may be placed in the field to enhance the clarity and reliability of the documentation. The use of robust reference systems is crucial to ensure accuracy and consistency in this process, even though it is not mandatory.

Cadastral survey workflows vary across countries due to differences in legislative frameworks, organisational structures, mandates, technological development, and the parties involved. Despite these differences, key activities can be identified, allowing for constructive conclusions to be drawn, leading to the development of a generic approach that can accommodate diverse national contexts.

It is noted that in the context of this research, a workflow is defined as the computer implementation or automation of a business process. A system that fully defines, manages, and executes workflows by performing activities in a predefined sequence, guided by workflow logic, is referred to as a Workflow Management System (WFMS), in line with definitions by Vranić et al. (2021).

The reference cadastral workflow developed within this dissertation is presented in two main figures. Figure 6.16, which presents the overview of the generic steps in the cadastral survey workflow, and Figure 6.17 that further details in the data collection phase.

Figure 6.16, depticts the overview of the generic steps in the cadastral survey workflow, aiming to document rights over spatial units with agreement between all involved parties, such as surveying professionals, as well as citizens, and neighbours sometimes supported by survey professionals.

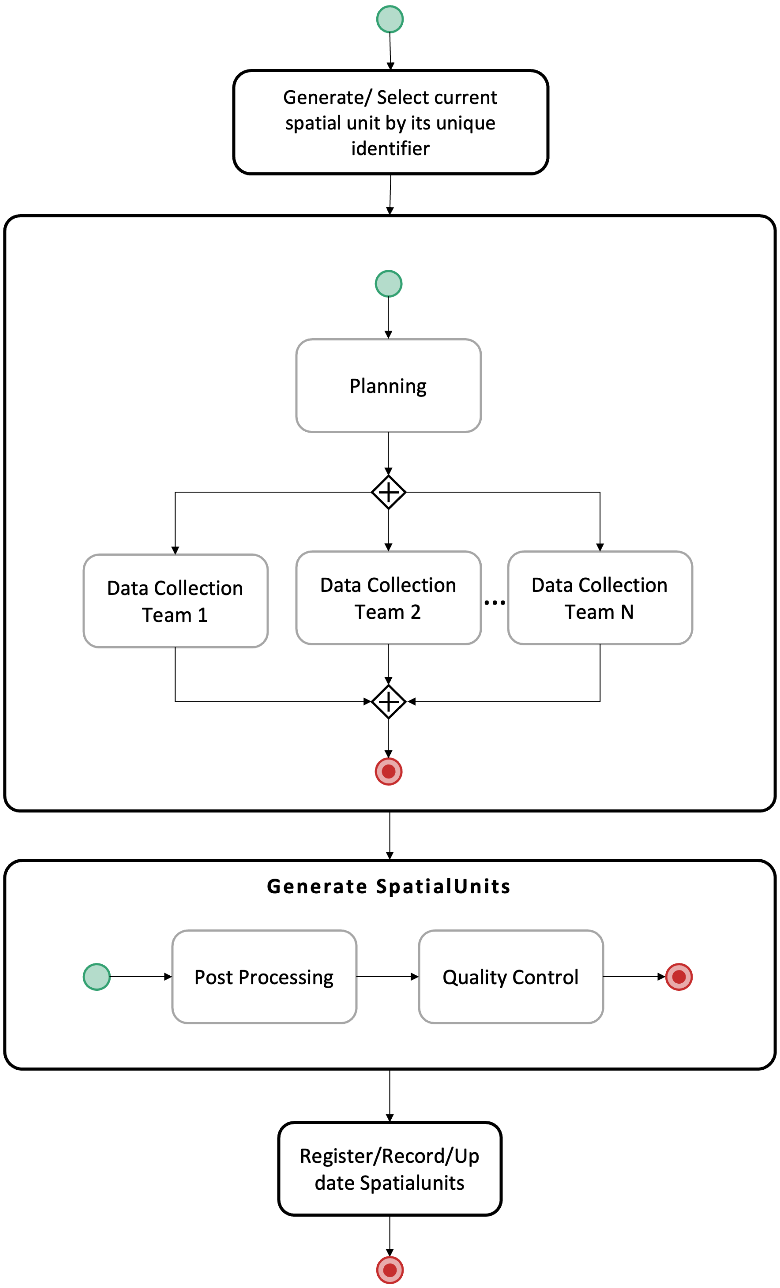

FIG. 6.16 Generic steps of the reference cadastral survey workflow in line with the LADM survey model

The workflow includes the following activities:

First, previous boundary-related sources, such as fieldwork records, maps, and other relevant documents, are collected as needed, along with obtaining necessary permissions. The next step involves identifying the new boundaries of spatial units where rights apply. These boundaries may be physically marked or staked out if needed and are surveyed in a national reference system and locally well-defined points, with aerial survey results being utilized where applicable. Once boundaries are identified and surveyed, the documentation of the boundary surveys is prepared in appropriate formats. The documentation is then presented to all involved parties for confirmation, ensuring accuracy and mutual agreement. Following this, the relevant agencies review, approve, and archive the documentation to formalize and preserve the records. Finally, the surveying process is concluded, with all parties involved agreeing on the outcome and formally closing the effort.

The cadastral survey workflow begins with identifying the specific "case," meaning the project, or the survey activity. The workflow then starts with planning the data acquisition process in a defined area. This area may be a project site for initial data collection or a set of spatial units requiring data maintenance. Depending on the survey's purpose, the area's size, and the equipment to be used, decisions are made regarding the number of teams required to work in the field for data collection or maintenance, as well as setting out designed spatial units or boundaries.

The field teams proceed to collect spatial data or simultaneously perform the setting out of spatial units or boundaries, as well as collect administrative/legal data. In the post-processing stage, observations are adjusted to existing point coordinates and/or transformed into topologically correct representations of the spatial units. The final step in the workflow is the recordation or registration of the processed data into the (official) cadastre and land registry.

Figure 6.17, further details into the steps of Figure 6.16 and illustrates the data collection process of this workflow, aligning with the LADM survey model.

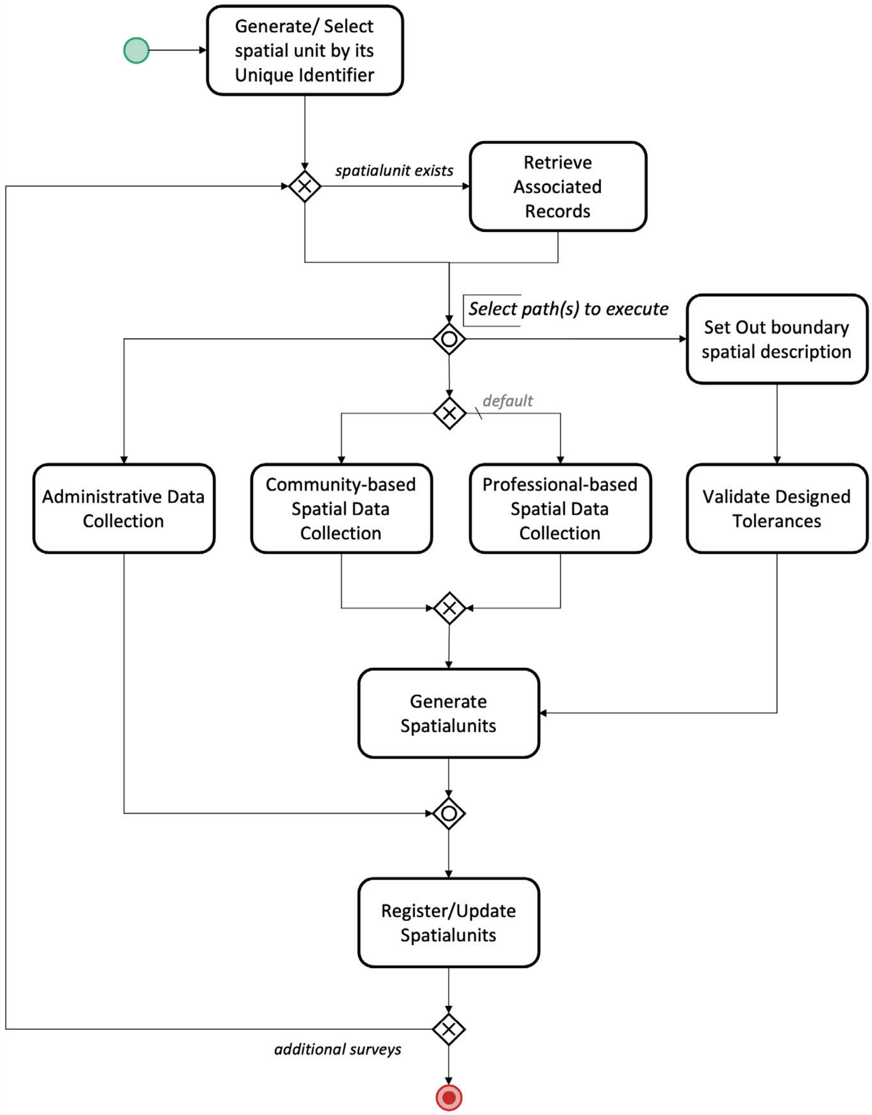

FIG. 6.17 Detailed steps of the reference cadastral survey workflow presented in Figure 6.16.

The notations used in Figure 6.16 and Figure 6.17 are explained in Table 6.1 (OMG, 2011):

TABLE 6.1 Notations used in the activity diagrams describing the reference cadastral workflow

Symbol	Reference cadastral workflow
	An **inclusive gateway** allows multiple sequential flows to evaluate to true hence enabling the process to follow various paths depending on the evaluation of the gateway criteria for each process instance.
	An **exclusive gateway** always leads to the activation of exactly one sequential flow. If none of the gateway's conditions evaluates to true, then the default path is activated.
	A **start event** represents the point at which a process instance or a sub-process starts.
	An **end event** represents the point where the process or sub-process is considered to be completed successfully.
	An **activity** corresponds to a process step that can be atomic or decomposable into a sub-process.

The data collection process begins with defining unique identifiers for newly created spatial units or retrieving existing identifiers if spatial units already exist. Similar actions are taken for party identifiers. These identifiers enable independent collection of administrative and spatial data, which are later merged during the survey process. For existing spatial units, related information can be retrieved either from design sources (e.g., BIM models, spatial plans, or land consolidation plans) or survey sources (e.g., cadastral databases/registries). This aligns with the two new subclasses of “LA_SpatialSource” in LADM Edition II-Part 2: “LA_DesignSource” and “LA_SurveySource” (Figure 6.12) introducing the concept of reusing information from multiple sources.

Following this step, three processes can occur in parallel, each of which is optional:

- Collection of administrative information: This involves collecting relevant data on parties and/or rights, which may vary based on the availability of existing sources. In some cases, all data attributes on parties and rights may need to be newly created. Administrative data may also be distributed in cases of spatial planning.
- Collection of spatial information for the boundaries of the spatial units: This process involves spatial data acquisition, which may be sourced directly from survey activities. Data acquisition can be executed either through a participatory approach (e.g., community-based spatial data collection supervised by professionals) or directly by professional surveyors using various methods represented by subclasses of the “LA_SurveySource.”
- Setting out designed boundary descriptions: This involves marking or validating spatial coordinates from design sources. Depending on regulations and the legislative framework, validation is performed to ensure results fall within acceptable tolerances. If validation fails, redesign may be required. The final stage for spatial

TOC

data collection and setting out designed coordinates involves creating new spatial units or updating existing ones. These units are then used to either modify current records or generate new entries, contributing to a comprehensive and updated cadastral registry.

6.5 Discussion

The advancement of digital technologies, such as GIS, BIM, unmanned vehicles, and laser scanning, has revolutionised the collection and management of 3D spatial data, making it more accessible and cost-effective. These technologies facilitate the creation of detailed, accurate 3D models' representation of spatial units, which can be seamlessly integrated into LASs, thereby enhancing decision-making processes and operational efficiency.

The **findings presented in this chapter** underscore the critical role of technological innovation in cadastral surveying and eventually LASs. By enriching **3D spatial profiles**, refining the **LADM survey model** and developing a **generic cadastral survey workflow**, the research demonstrates a path forward for improving the documentation and management of people-to-land relationships. These developments enable LASs to address global challenges and meet the evolving needs of societies. The developed models and methodologies not only advance scientific knowledge, but also offer practical solutions for improving LA efficiency worldwide.

Addressing **Sub-RQ3b "How can the 3D spatial units be described in a standardised way?"**, this chapter presents the preparation of contents for 3D spatial profiles for the new international standard ISO 19152-2. These profiles respond to the increasing demand for detailed 3D representation and registration, as they support complex geometries and accommodate country-specific needs, facilitating broader interoperability across disciplines and lifecycle phases. The support for 3D spatial units fulfils the requirements outlined in sub-section 4.2.1, specifically Requirement 2-12, 'Continuum of Spatial Units', supporting the representation of a broad range of spatial units, with a clear quality indication.

Moreover, to address **Sub-RQ4b "Based on the cadastral surveying requirements, how can the survey model for LADM Part 2- Land Registration be developed?"** and **Sub-RQ5 "How can a generic, reference LA workflow be designed, built upon the survey model for LADM Part 2- Land Registration?"**, the cadastral survey model and the reference cadastral workflow developed in this dissertation, address the recording of the dynamic and complex nature of people-to-land relationships. They integrate participatory land-rights recordation processes alongside professional data collection methods and incorporate HAS capabilities, demonstrating significant progress toward achieving greater inclusivity, precision, and adaptability. This flexible and forward-looking approach enables the spatial source concept in LADM to support diverse surveying methodologies while adhering to established international standards such as OGC LandInfra and ISO 16739-1:2024 IFC. The LADM survey model facilitates frequent updates and modifications, which are essential for maintaining the legal and spatial integrity of land rights. A key innovation of this contribution is the incorporation of HAS, which provides globally available satellite-based corrections at no cost (in middle 2025). This technology enhances the precision of spatial data acquisition and enables more reliable boundary delineations, particularly in applications requiring high accuracy and scalability.

The LADM survey model incorporates the ability to optionally record coordinate or vector uncertainties along with their associated metadata through the LA_GNSSCorrection class. This feature supports the integration of corrections for GNSS observations as a (not obligatory) component, enabling the generic modelling of HA) elements. These corrections aim to improve the precision of satellite navigation signals. Currently, HAS offers free and globally available corrections for precise positioning tailored to GPS and Galileo systems, specifically designed for use in Precise Point Positioning (PPP) algorithms. Additionally, other GNSS systems are actively developing or have already implemented similar high-accuracy services. The inclusion of OSR and SSR approaches further strengthens the model by providing a standardised and modular framework for transmitting and applying corrections. This design ensures compatibility across diverse GNSS services and enhances the reliability and accuracy of spatial data acquisition. What is more, the LA_DesignSource subclass further supports the reuse of data from the design phase.

The *inclusion of participatory approaches*, where communities actively contribute to data collection under professional supervision, represents a shift toward democratising LAS. These methods are especially valuable in regions where traditional surveying techniques may not be economically or practically feasible, such as large areas lacking documented rights. Both the developed cadastral survey workflow and the survey model are technology-neutral, capturing 3D coordinates along with their associated uncertainties. This is supported by various sub-classes introduced in LA_SurveySource, which represent different methods of observations' acquisition.

Finally, the **development of a reference cadastral survey workflow** bridges administrative and technical aspects, accommodating diverse national contexts in line with the conceptual survey model of ISO19152-2:2025. This structured approach fosters collaboration among stakeholders, including professionals, citizens, and regulatory agencies, while ensuring reliable land-rights documentation. The workflow and the survey model meet the requirements outlined in sub-section 4.2.1 and support both 2D and 3D data acquisition techniques and processes. These include maintaining spatial data within spatial data infrastructure (Requirement 2-5), ensuring unique identifiers for spatial units and records (Requirement 2-13), supporting spatial sources such as surveys and design documents (Requirement 2-14), providing multiple surveying methods (Requirement 2-15), supporting coordinate transformations (Requirement 2-16), and ensuring data quality and consistency (Requirement 2-17). The inclusion of quality control steps in the workflow further emphasizes the importance of data reliability and accessibility.

The results of this chapter are acknowledged by standardization organizations and have already been or will be incorporated into various parts of ISO 19152. Specifically, the 3D spatial profiles are included in Annex C of ISO19152-2:2025, the refined survey model is a key component of ISO19152-2:2025, while the reference cadastral workflow is planned for inclusion as Part 6a of ISO19152-6.

PART III

Development and evaluation

7 Developing LADM Methodology: Insights from 3D LA and LADM International Experience

[Sub-RQ1a] **What is the current state-of-the-art in standardisation in (2D and 3D) Land Administration around the world, as documented byreported by countries?**

[Sub-RQ6] **What steps should a country follow to develop a LADM-based country profile**

This chapter is based on the following publications:

Kalogianni, E., *van Oosterom, P.J.M., Lemmen, C.H.J., Ploeger, H., Thompson, R.J., Karki, S., Shnaidman, Rahman, A.A. (2023). 3D Land Administration: Current Status (2022) and Expectation for the Near Future (2026) – Initial Analysis. In Proceedings: FIG Working Week 2023.*

Thompson, R.J., ***Kalogianni, E.****, van Oosterom, P.J.M. (2023). Analysing 3D Land Administration developments and plans from 2010 to 2026. In Proceedings: 11th International FIG Workshop on LADM/3D LA, pp. 119-132, part of ISBN: 978-87-93914-09-4.*

Kalogianni, E., *Janečka, K., Kalantari, M., Dimopoulou, E., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., Govedarica, M., Lemmen, C.H.J., van Oosterom, P.J.M. (2021). Methodology for the development of LADM country profiles. Land Use Policy, 105, 105380. doi: https://doi.org/10.1016/j.landusepol.2021.105380.*

ABSTRACT Section 7.1 explores the ongoing adaptation of 3D LAS, highlighting the drivers, challenges, and plans based on the responses to the 4th FIG Questionnaire on 3D LAS (2022–2026), shaping this transition. This section offers a detailed overview of the evolution of LAS practices worldwide, supporting the shift to 3D systems to

meet the demand for efficient spatial management, particularly in urban and densely populated areas. It categorises the priorities and readiness of countries into three main aspects: legal, organisational, and technical.

The country profiles developed across different jurisdictions that have been presented in section 4.3, create a diverse "mosaic" of methodologies for implementing the LADM, with valuable lessons to be drawn from each. A set of generic characteristics applicable to all country profiles is derived in section 7.2, encompassing legal, institutional, and technical issues and considering all stages profile development and implementation. This approach ensures that the design of country profiles is grounded on empirical evidence and collective experience. By analysing commonalities and differences among country profiles, this comparative approach extracts key insights and best practices that inform future profile design. These findings provide a basis for developing a robust methodology to support the design, validation, and implementation of LADM-based country profiles.

Building on this, section 7.3 proposes a methodology for developing LADM-based country profiles, emphasising an iterative process, including scope definition, profile creation, and testing. This methodology balances a generic approach with the flexibility required to accommodate the unique legal, cultural, and geographical differences between regions. Designed to be adaptable, the methodology evolves alongside advancements in technology and emerging needs in LA, providing a robust framework for future development efforts.

The chapter concludes with a discussion in section 7.4.

7.1 3D LAS around the world: expectations till 2026

Following the analysis of the responses from 37 countries participating in the 4th FIG Questionnaire on 3D Land Administration 2022-2026 that has been presented in section 2.3, this section provides a comprehensive overview of the evolution and current state of global LA practices, with a focus on the shift to 3D systems. The current section lays the groundwork for understanding the future directions of participating countries in 3D LA. It highlights the need to integrate advanced technologies and standardisation efforts to address the growing demand for effective space utilisation in built-up areas.

TOC

The priorities identified by each country in the field of LAS from 2022 till 2026, have been compiled and summarised in Table 7.1. The challenges reported by the participants can be categorised in the following three groups:

1. **Legal aspects:** These challenges pertain to the establishment of a legislation in support to the use of framework that supports 3D LA. This may require adapting existing laws or enacting new laws to manage the complexities of 3D representations in LA effectively.
2. **Organisational aspects:** These include building the capacity of personnel to effectively operate and manage 3D LAS. They also involve engaging the private sector and other stakeholders in the process and in the development of clear and actionable guidelines to facilitate smooth implementation.
3. **Technical aspects:** These focus on developing software solutions and in ensuring interoperability between various datasets and systems. The challenges also encompass the adoption of cutting-edge technologies such as virtual reality (VR) and augmented reality (AR) and providing robust support to the capture, management, and dissemination of 3D surveying data.

TABLE 7.1 Priority axes for the period 2022-2026 related to the developments of 3D LAS, per country (only the countries that have provided data are presented)

#	Countries reported their top priorities for 2026	Priorities axes
1	Argentina	• development of the concept of 3D property and parcels, • incorporation of 3D GIS platforms into cadastral institutions, • integration of LADM concepts into public cadastral institutions.
2	AUS – NSW	• data standards and interoperability • addressing software limitations and strengths, • securing industry and stakeholder support for reform.
3	AUS – Queensland	• digital submission of surveying information.
4	AUS – Victoria	• legal and cultural shift towards 3D environments, • addressing technical issues such as 3D data management, validation, integrity, and visualisation (VR/AR), and developing guidelines for 3D data capture by surveyors.
5	Bahrain	• addressing cost and training, • enabling the private sector to produce accurate as-built data, • improving data dissemination and sharing.
6	Canada-Quebec	• spatial representation of overlapping properties, • integration strategies for real estate (registered and unregistered), • modernisation of stakeholder practices, • evolving laws and regulations.
7	Croatia	• capacity building in LA, • conducting new types of cadastral surveys, • capturing and maintaining height and volume data.

>>>

TABLE 7.1 Priority axes for the period 2022-2026 related to the developments of 3D LAS, per country (only the countries that have provided data are presented)

#	Countries reported their top priorities for 2026	Priorities axes
8	Cyprus	• technical approaches for data capture, • data model design, • managing the cost of implementation.
9	Czech Republic	• sourcing 3D data for 3D parcels (e.g., using BIM), • demonstrating the benefits of 3D parcels through visualization, • addressing legislative needs.
10	Finland	• development of 3D right-of-use units (spatial units that define specific RRRs).
11	Kenya	• formalising an LADM profile for 3D systems, • harmonising coordinate systems for cadastral data, • creating guidelines for implementing a digital 3D cadastre.
12	Malaysia	• addressing data availability and legal aspects.
13	Montenegro	• raising awareness about the need for 3D cadastres despite existing research on possible solutions.
14	Nepal	• establishing a strong legal framework, • improving technical capabilities for 3D data acquisition, • integrating visualization in cadastral information systems.
15	New Zealand	• addressing costs and efforts related to developing *Landonline*[29] for 3D parcels, • reducing dependency on third-party software vendors for the creation and supply of 3D data for survey and title purposes, • supporting surveyors during the transition to 3D systems.
16	Poland	• enacting laws for multilayer property.
17	Serbia	• building awareness for the need for 3D cadastres.
18	Singapore	• formalising legislation for implementation of vertical dimensions, • addressing mindset changes among agency officers and surveyors, • accelerating software development for 3D submissions.
19	South Korea	• developing 3D cadastral laws, • addressing societal demand for 3D systems.
20	Sweden	• developing standards for 3D GIS in LA, • incorporating BIM, • improving capacity, resources, and technical possibilities.
21	Switzerland	• adapting the legal framework, • developing a cadastral surveying data model, • providing education and training for professionals.
22	The Netherlands	• establishing a robust legal framework (in the Civil Code), • addressing technical implementation and costs, • focusing on system maintenance.
23	Trinidad and Tobago	• convincing the Government for the need and the benefits of 3D Cadastre, • systematic adjudication and titling, • implementing condominium legislation, • securing financial support and capacity building for personnel.
24	Turkey	• availability of 3D data and quality of cadastral data, • addressing legal challenges.

29 https://data.linz.govt.nz/layer/51976-landonline-parcel/

Legal challenges are a prominent concern, with many countries emphasising the need to establish or adapt legislation to support 3D LA. For instance, Switzerland, The Netherlands, Singapore, and Poland require legal frameworks to address vertical property rights, multi-layered ownership, and formalised 3D-specific laws. Additionally, countries such as Croatia and Kenya report the need to convince stakeholders, including lawmakers and professionals, of the importance of legislation in support to 3D LA.

Organisational and capacity-building challenges are also evident and mentioned by countries like Croatia, Singapore, and Trinidad and Tobago highlighting the importance of education, training, and professional development to equip surveyors and other stakeholders for the transition to 3D systems. Stakeholder engagement, including collaboration with the private sector and fostering support from governments and industries, is identified as a priority by countries such as Bahrain and Trinidad and Tobago.

Technical challenges are a recurring theme, as indicated by Argentina, New Zealand, and Sweden prioritising the development of 3D GIS platforms, enhancing interoperability, and integrating advanced tools like BIM. Many countries, including Cyprus, Czech Republic, and Kenya, emphasise the need for robust data models and tools to effectively manage 3D datasets. Furthermore, the adoption of modern technologies such as VR, AR and improved software capabilities is prioritised by Australia (Victoria) and Malaysia.

Financial constraints and resource allocation present additional barriers, as mentioned by countries such as New Zealand, Cyprus, and Trinidad and Tobago, where the potential high cost of developing or maintaining 3D LAS is recognised as a significant challenge. Cost-related training and infrastructure investments are also emphasised, particularly by Bahrain and Nepal.

Lastly, cultural and institutional shifts are required to enable the transition to 3D LAS. Singapore and Australia (Victoria) highlight the need to change mindsets among surveyors, government officials, and other stakeholders. This involves not only technical adjustments but also fostering a cultural shift toward embracing and adopting 3D technologies.

7.2 Criteria and comparative analysis of the LADM-based country profiles

By narrowing the focus of the previous sub-section to (3D) LAS based on LADM, and by utilising the systematic collection of LADM-based country profiles as detailed in section 4.3, this sub-section defines the criteria for conducting a comparative analysis of these profiles. The goal of this analysis is to extract good practices to be used as basis of a comprehensive methodology for the creation of country profiles for both LADM Edition I and Edition II. To understand the process behind the development of the criteria and the subsequent methodology for LADM country profiles, Figure 7.1 illustrates the method followed.

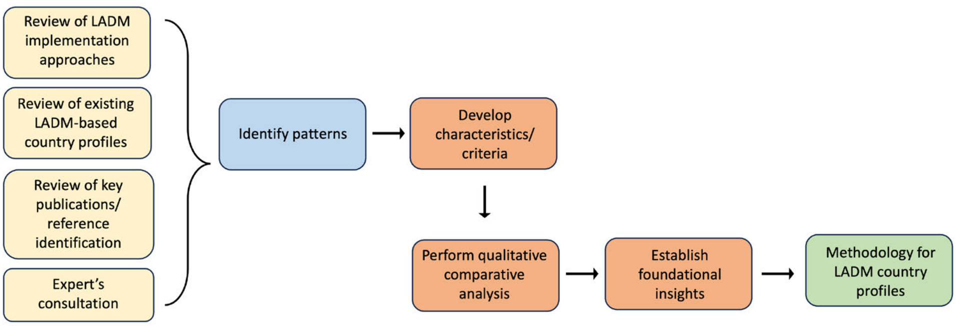

FIG. 7.1 Method followed for the development of criteria, comparative analysis and LADM country profiles methodology

The method for designing LADM-based country profiles begins with a literature review and analysis of documentation on existing profiles and their respective technical implementation approaches. This research focuses on country profiles developed between 2012, when LADM Edition I was first published, and 2020, during the ongoing revision of LADM Edition II. The findings from this review are analysed in section 4.3. To complement this analysis, consultations with experts and interviews with key stakeholders, including the Editors of Edition I and Parts of Edition II and developers of country profiles, are conducted. These interactions provide valuable insights, highlight essential references, and contribute to the understanding of the approaches taken in the profile development.

Using the combined results from the literature review and expert consultations, a set of criteria is developed to identify good practices within the development of existing profiles. They are designed to evaluate the profiles' structure, implementation approaches, and alignment with LADM's core principles and serve as criteria for performing a quantitative comparative analysis of a representative subset of country profiles. This analysis involves scanning the profiles to detect patterns, similarities, and discrepancies in their development approaches.

Sub-section 7.2.1 presents the five criteria crucial for developing LADM-based country profiles, while sub-section 7.2.2 describes a comparative analysis performed to a selected sub-set of country profiles.

7.2.1 Criteria for developing and assessing existing LADM-based country profiles

To start with, the analysis of background information led to the identification of five generic criteria crucial for developing LADM-based country profiles. These characteristics are:

1. **Profile Scope**, which defines the breadth and depth of the profile, considering also the anticipated extensions and applications of the profile.
2. **Stakeholder Involvement**, focusing on the level and diversity of engagement of relevant parties.
3. **Status of Existing LAS**, examining the current state of LAS in the country.
4. **Profile Development Stage**, detailing the progress and maturity of the profile development process (if it includes only mapping, or conceptual modelling or implementation).
5. **3D Land Administration**, addressing the 3D level of maturity of the profile.

I Profile Scope

The scope of a country profile can vary widely, depending on whether it aims to describe the current state of the national LA domain or present a vision for its future development. This distinction determines how the profile aligns with LADM concepts and the functionality it incorporates. Profiles describing the current situation typically adapt existing LAS to the LADM, building upon current cadastral data models. Examples of such profiles include those developed for Croatia, Czech Republic, Poland, Serbia, Montenegro, and the Republic of Srpska (as presented in Table 4.2), which rely on existing cadastral data to align with LADM.

In contrast, profiles describing a future state propose new functionalities and address data that may not yet be registered or is currently managed by other authorities, such as tax offices, mapping agencies, or municipalities. For instance, the profile developed for Greece envisions a multipurpose LAS that includes land and marine parcels, mines, archaeological sites, utility networks, and other functionalities beyond traditional cadastral systems.

The developed profiles can be further categorised into two primary groups based on their scope. The first group takes a holistic approach, aiming to model land-related information comprehensively across a wide range of applications, as seen in the profiles for The Netherlands and Poland. The second group focuses on specific applications of land information, such as natural resources in China or utility cadastres in Serbia. This categorisation highlights the flexibility of LADM-based country profiles to address diverse needs, whether through a comprehensive or targeted approach. Moreover, it is important to consider that Edition II includes five Parts with conceptual models (Part 1-5), which may be included at a future version of the country profile.

II Stakeholder Involvement

The development of LADM-based country profiles is a multidisciplinary process involving a range of stakeholders, including government or LA authorities, geodetic authorities, academic institutions and industry. Each group brings a unique perspective and expertise, shaping the outcomes. Profiles primarily developed by academia are often rooted in the conceptual schema of LADM, informed by good practices from jurisdictions with similar characteristics and adjusted to meet specific national needs. Examples of this academic-led approach can be observed in Croatia, the Czech Republic, Poland, and Serbia, where the initial development of country profiles was undertaken by academic institutions rather than national mapping agencies.

By 2020, analysis revealed that collaborative efforts between government entities and academia are relatively few. This collaborative model, however, is particularly valuable, as it aligns country profiles with theoretical standards while addressing practical implementation needs, thereby bridging the gap between conceptual frameworks and real-world application. Examples include the country profiles for Colombia, Korea, and Malaysia (as shown in Table 4.2), where academic and government stakeholders work together to create profiles tailored to their unique national contexts.

Conversely, some country profiles have been developed exclusively under the guidance of government authorities, reflecting a centralised approach to profile development. The country profile for Scotland is a prominent example of this approach. While this approach ensures direct alignment with national policy frameworks and operational priorities, it may not fully leverage the theoretical insights and broader innovations contributed by academia.

A challenge in the development of LADM-based profiles is ensuring effective knowledge sharing and replication of successful approaches. While LADM workshops provide extensive documentation on detailed data models, the continuous maintenance and updating of this documentation is important. To address this, development teams should include professionals with comprehensive knowledge of the LA domain, often from governmental organisations.

III Status of Existing LAS

The status of existing LAS significantly influences the approach adopted for implementing LADM. The maturity and functionality of the LAS influence the way in which LADM principles are applied. Kalantari et al. (2015) proposes a six-stage roadmap for adopting LADM, which includes key factors that LA organisations could consider. These factors include organisational motivation, institutional arrangements, governance and capacity building, as well as technical aspects such as data organization.

Notably, more mature LAS systems typically align with Stage 4 “Data Organisation” of Kalantari et al. (2015) roadmap. This stage emphasizes the structuring and interlinking of diverse data entities within the LAS, ensuring that the system is well-equipped to support efficient and accurate land administration processes. By addressing data organization at this level, mature LAS can fully leverage the benefits of LADM by ensuring data interoperability and consistency.

In Serbia, Montenegro, and the Republic of Srpska in Bosnia and Herzegovina (as shown in Table 4.2), the primary objective of adopting LADM is to modernise existing LASs and resolve critical deficiencies. Key issues in these systems include overlapping responsibilities among institutions managing land-related information, data storage at multiple locations or in analogue formats, reliance on non-relational data models, discrepancies between recorded data and the actual situation on the ground, and the separation of alphanumeric and geometric data. Additionally, these systems often suffer from complex record structures inherited from diverse sources, poor performance in data searching and updating, and reliance on outdated legal concepts such as immovable property definitions embedded in legacy software solutions.

These challenges have hindered the operational efficiency and data quality of the LAS, rendering them functionally inadequate despite being formally established and operational. Consequently, require a redesign could be considered in such systems to address these inherited deficiencies, improve data reliability, and align with contemporary LA practices guided by LADM Editions.

IV Profile Development Stage

The development stage of a country profile reflects whether the modelling process is at a conceptual level or extends to implementation (prototype, pilot or operational system). The examined country profiles vary not only in their stages of development but also in the specific steps taken to achieve their current state. In countries with well-established LAS, the process typically begins with the physical data model of the existing cadastral database. Through reverse engineering, as described by Janečka et al. (2017), a conceptual cadastral data model is derived, which serves as the foundation for the profile's conceptual model.

In most country profiles outlined in Table 4.2, conceptual models are developed using UML diagrams. These models integrate the three core packages of LADM, tailored to meet local requirements, while the Surveying and Representation sub-package is generally used as specified in the ISO standard. Beyond these core elements, several profiles incorporate extensions to address specific national needs, such as inclusion of land use components, or registration of utility networks, and processes, which complement the static structure of the data model.

Once a UML model for a country profile is created, its conformity with ISO 19152:2012 (Edition I) or ISO 19152-1:2024 (Edition II) is verified through conformance testing as outlined in the respective Annexes A. The subsequent technical implementation varies among country profiles and ranges from initial prototypes and pilot projects to fully operational production systems. Typically, the development process involves translating the conceptual model into a technical implementation, converting and loading datasets into a database, and developing a LADM-compliant database schema. This is followed by the creation of applications to support the required system functionality.

Each phase of implementation generates new insights, which contribute to the iterative refinement of the country profile. As stakeholders become more engaged and gain a deeper understanding of the system, the conceptual model is continuously enhanced. This iterative improvement process is often facilitated through inter-institutional modelling workshops, ensuring that the country profile accurately represents real-world conditions and meets the specific needs of its users. This approach highlights the dynamic and adaptive nature of LADM-based country profile development, where continuous feedback and collaboration drive improvements in both conceptual and technical aspects.

V Aspects related to 3D Land Administration

This characteristic distinguishes between 2D and 3D spatial representations and defines how a country profile relates to 3D physical counterparts in LA. LADM Edition I supports the registration of 3D spatial units, enabling countries to model and manage land-related information in three dimensions where necessary, while LADM Edition II further strengthens the 3D support through more 3D spatial profiles (section 6.2). Several LADM-based country profiles already incorporate 3D capabilities, including those for the Russian Federation, Poland, Malaysia, Israel, Greece, Trinidad and Tobago and Turkey, as presented in Table 4.2.

From the analysis of these profiles, it is evident that many countries consider inclusion of 3D LA into their systems, often providing options for both 2D and 3D spatial representations.

7.2.2 Comparative analysis

A subset of country profiles, as presented in Table 7.2, has been selected for an in-depth analysis concerning the identified characteristics. These profiles have been chosen for their completeness and the quality of their documentation, making them exemplary cases for evaluation. They encompass a wide range of LASs and demonstrate developments that integrate contributions from various stakeholders, including governmental experts, scientists and professionals from industry.

TABLE 7.2 Comparative Analysis of the characteristics on a representative subset of LADM-based country profiles

Country	Scope of the profile	Stakeholders	LAS Status	Profile Development Stage	3D LA
Colombia	PCS	Ac & Gov	Est & Mod	UML & TI	2D
Croatia	CS & FS (including MC)	Ac	Est	UML	2D & 3D
Czech Republic	CS	Ac & Gov	Est	UML	2D
Malaysia	CS	Ac & Gov	Est	UML & TI	2D & 3D
Montenegro	CS	Ac & Gov	Est	UML & TI	2D
Poland	CS & FS	Ac	Est	UML	2D & 3D
Republic of Srpska	CS	Ac & Gov	Est	UML & TI	2D
Scotland	CS	Gov	Est	UML & TI	2D & 3D
Serbia	CS (including current UNC)	Ac & GA	Est	UML	2D

CS: *current situation,* ***FS:*** *future situation,* ***PCS:*** *post-conflict situations,* ***Ac:*** *academia,* ***Gov:*** *government,* ***GA:*** *geodetic authorities,* ***Est:*** *Established,* ***Mod:*** *Modernised,* ***UML:*** *UML model,* ***TI:*** *Technical Implementation,* ***MC:*** *Marine Cadastre,* ***UNC:*** *Utility Network Cadastre*

The table highlights the ability of LADM to accommodate distinct stages of development and varying scopes of application, demonstrating its relevance across diverse national contexts. The comparative analysis confirms that the identified characteristics are highly applicable to these profiles, underscoring their relevance in evaluating and guiding the development of LADM-based country profiles.

By presenting this comparison, the table provides insights into the methodologies, stakeholder involvement, and implementation strategies employed in different jurisdictions. These insights not only reflect the diversity in LAS development but also highlight good practices that can inform future profile creation. The integration of conceptual models, technical implementation, and extended functionalities, such as 3D representations and specialised LAS, further emphasises the versatility of LADM.

7.3 Methodology to develop LADM-based country profiles

The methodology for developing an LADM country profile builds on research and technical knowledge from analysing the prior implementations, integrating both technical and non-technical aspects. The technical foundation includes principles of data modelling and the use of UML notation, while the non-technical aspects emphasise domain expertise, process understanding, and consideration of institutional and legal frameworks. This methodology distils good practices from existing profiles and is structured into three iterative phases (Figure 7.2):

1. **Phase I – Scope Definition:** This phase focuses on defining the scope of the profile, identifying the spatial units, stakeholders, processes, and institutional requirements that the profile will address.
2. **Phase II – Profile Creation (Modelling):** This involves the conceptual design of the profile using UML diagrams, capturing the LADM concepts and terminology and aligning it to the existing national situation.
3. **Phase III – Profile Testing (Implementation):** In this phase, the profile undergoes testing through implementation, evaluating its functionality and efficiency. Feedback from this phase often leads to further refinements, by iterations through Phase I or Phase II.

This iterative methodology applies to both Editions I and II of LADM, ensuring that the development process remains adaptive to new requirements and insights. The use if the versioning option of the profiles is an important consideration within this methodology. Many profiles developed during the early stages of LADM Edition I development, such as those for Israel and Indonesia, have undergone subsequent updates to improve and enrich those initial versions. The versioning process involves creating an initial profile (Version I) that captures the LADM terminology and usually aligns with the operational system through reverse engineering. This serves as a foundation for updates to the next version (Version II), which may involve adding or removing elements, broadening the scope or focusing on specific topics, or otherwise enhancing the initial model.

The methodology remains consistent across profile versions, with the existing UML model serving as the basis for updates in Phase II. Figure 7.2 further illustrates the iterative relationships between the three phases, emphasising how they interconnect to support the development of any version of a LADM profile.

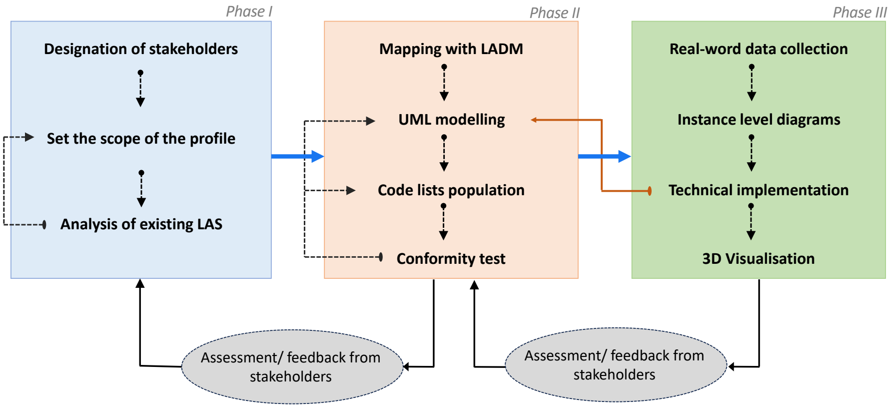

FIG. 7.2 Phases of the LADM-based country profile development

The following sub-sections describe in detail the context and steps involved in each phase, providing a framework for creating, refining, and implementing LADM-based country profiles. This structured approach ensures that profiles remain aligned with the evolving needs of LAS, while adhering to the principles of LADM Editions.

7.3.1 Phase I – Scope Definition

In the first phase of the development process, the scope definition is a critical decision that directly influences the involvement of stakeholders and the design of the profile (Figure 7.3, Ib). The scope determines whether the model will describe the existing situation, a future situation, or both. Especially for Edition II, it also involves the decision on the Parts of LADM that will be developed (mainly, tenure, value, marine, spatial plans).

Consequently, this impacts the identification of stakeholders, as the process of defining the project scope and identifying stakeholders is inherently interdependent. To address this, an initial core team of key stakeholders is typically formed. This core team often includes representatives from LA authorities managing cadastral systems, academia and relevant government organizations. As the project scope broadens or evolves, the process remains flexible, allowing for the inclusion of additional stakeholders. Indirect involvement, such as through interviews or consultations, can also provide valuable input from other interested parties.

The fundamentals for developing a LADM country profile depend on the status of the LAS and its documentation. In jurisdictions with a functioning LAS, UML models of the existing system provide a valuable starting point. These models already define core classes, such as spatial units and parties, and the associations between them, enabling a more direct focus on mapping or generalising these elements in order to align with LADM. Simplification of these existing UML diagrams can be carried out if needed.

In cases where UML diagrams or the database schema of the existing LAS are unavailable or inaccessible, the profile development must begin from scratch. This typically involves reverse engineering based on the physical data model or leveraging documentation and legal definitions of the LAS provided by various legislative and regulatory frameworks. An early step in such cases involves analysing requirements defined in national legislative frameworks and other relevant regulations. This analysis facilitates the derivation of RRRs, which are core elements of LADM, from the existing legal structure.

However, governments aiming to include additional concepts -not currently part of their LAS- for instance protected sites, utilities, spatial plan information, valuation information, marine spaces, or air parcels, can benefit from the Parts and extended packages introduced in LADM Edition II. These packages provide the flexibility to include such elements, ensuring that the profile can accommodate broader and more specialised information requirements.

This phase underscores the importance of tailoring the development process to the specific status and needs of the jurisdiction. By aligning with existing systems where possible or building from legal and regulatory foundations where necessary, the scope definition phase sets a solid groundwork for creating a country profile.

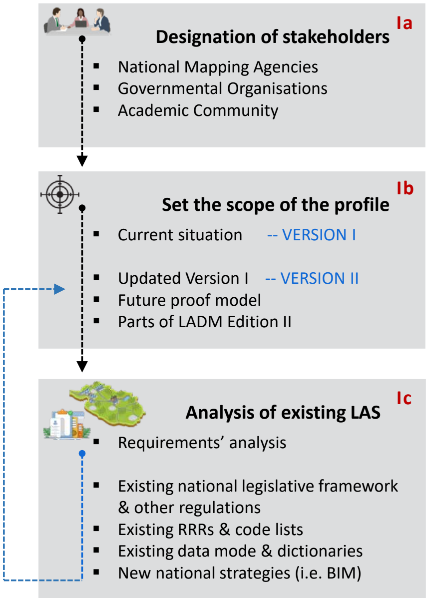

FIG. 7.3 Phase I - Scope definition of the LADM country profile methodology

7.3.2 Phase II – Profile Creation

The first step in this phase involves mapping the key concepts of the LA model with LADM classes (Figure 7.4, IIa). This step is critical as it forms the foundation for conceptual modelling, but in some cases it can be challenging due to the lack of a straightforward one-to-one correspondence between existing concepts and LADM classes. In some cases, multiple classes or concepts from the current model may map to a single LADM class, or there may be no direct equivalent.

The conceptual modelling phase of the profile focuses on accurately representing the country's existing LAS with LADM concepts. Initially, the development can focus on core LA concepts (land tenure and registry), with a particular emphasis on application of national semantics. The more extensively LADM core classes are utilised, the simpler and less complex the profile becomes, as one of LADM's objectives is to provide generic classes applicable across various LA domains globally.

Further categorisation may be considered, or the profile could be extended with new classes to capture specific legal and institutional requirements unique to the country.

A key decision to be made during this phase concerns the language and terminology to be used in the UML model (Figure 7.4, IIb). This decision determines whether class names, attributes, and associations in the UML diagrams will remain in English or are to be translated into the national language(s). The selected terminology must be clear enough to convey the intended concepts to both domain specialists and external audiences.

Key aspects of conceptual modelling include adapting prefixes for country-specific classes based on ISO 3166 country codes, defining code lists, and incorporating country-specific semantics. The modelling should be conducted in UML using software tools that support the MDA approach.

During the conceptual modelling, the following activities are carried out:

1. Inheritance from LADM (core) classes: Introduce inheritance relationships between country-specific classes and LADM (core) classes, applying country prefixes for clarity, based on ISO 3166.
2. Schema mapping: Explicitly map country profile classes to LADM (core) classes where inheritance is not applicable.
3. Creation of new classes: Add new classes to address specific national needs that are not supported by LADM.

4 Language translation: translate classes names and attributers into the national language.

5 New attributes: Extend LADM (core) classes with attributes that meet local requirements. New parameters can be added in the form of attributes, if needed.

6 New associations: Define relationships specific to the jurisdiction's needs.

7 Adjust multiplicities and constraints: Modify these elements of the model to represent national requirements and define constraints as needed.

8 Code Lists: Extend existing code lists and create new ones if required for new attributes (Figure 7.4, IIc).

9 External classes: Link to external classes to integrate the model with current registries and external systems (via SDI/ GII).

10 Conformance testing: Test the conformity of the conceptual model against the criteria outlined in Annex A of the ISO 19152-1:2024 (Figure 7.4, IId).

In order to streamline the modelling process and minimise the number of iteration rounds, it is recommended to establish a modelling working group -if possible- through inter-institutional agreements. These activities ensure that the conceptual model aligns with both the LADM and the specific needs of the country/ jurisdiction.

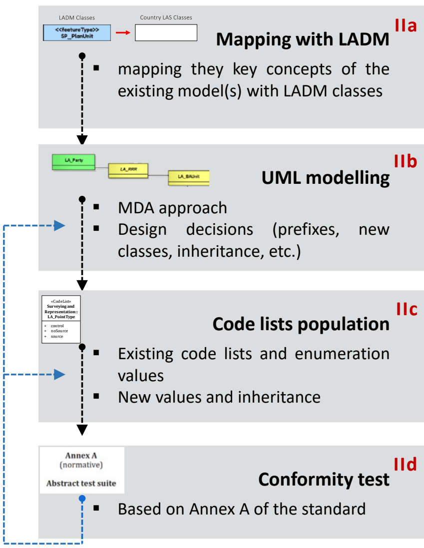

FIG. 7.4 Phase II – Profile Creation of the LADM country profile methodology

7.3.3 Phase III – Profile Testing

In addition to testing the profile at a technical level, it is also evaluated conceptually through the development of instance-level diagrams. These diagrams represent various use cases, helping to confirm that the conceptual model aligns with practical requirements and real-world scenarios. This dual-level validation supports the development of an LADM-based country profile that is both conceptually robust and technically reliable.

Once the country profile—preferably designed in UML—is finalised, it is typically translated into a corresponding database schema and managed within a software environment or directly implemented using technical encodings. This process involves mapping classes, data types, multiplicities, and associations from the conceptual model to the technical model. To ensure accuracy and consistency in implementation, specific transformation rules, parameters, and mapping entries must be defined, along with encoding rules for generating the target schema.

While some aspects of the conversion from conceptual to technical models, such as database schemas or exchange formats, can be automated (i.e. as supported by several software like Enterprise Architect), manual adjustments are often required. This is due to the differences in the expressive capabilities of UML class diagrams and the implementation schema languages. During this process, technical and performance-related considerations must also be addressed, including the implementation of primary/ foreign keys, association and attribute multiplicities, data types, spatial data types, indexes (including spatial indexes), constraints, and inheritance structures, as noted by Zulkifli et al. (2014) and Alattas et al. (2018). Such practical testing of the country profile may result in proposed changes at the earlier developed country profile and specifically at the UML conceptual model.

This phase generally results in the creation of an initial prototype or the deployment of an operational pilot system for a limited area or duration. Operating a pilot system in parallel with the existing system helps to mitigate risks in case any flaws arise in the new implementation. A successful pilot phase is crucial, as it demonstrates the system’s readiness for full-scale implementation.

Following the technical translation, sample data is prepared, either newly created or derived from existing LASs and registries (Figure 7.5 IIIa, IIIb), and loaded into the system (Figure 7.5 IIIc). This data is then used to test the system's functionality, including data access, updates, and integration through prototypes (Figure 7.5 IIId). The testing phase offers insights into the operational readiness of the system, allowing for further refinements before full deployment. The functionalities of the system may vary, ranging from simple data management to advanced 2D and 3D visualization capabilities, among others.

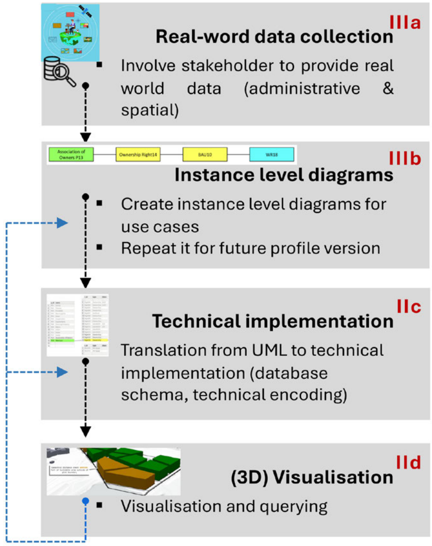

FIG. 7.5 Phase III – Profile Testing of the LADM country profile methodology

7.4 Discussion

This chapter provides an analysis of the transition towards a 3D LAS and the development of LADM-based country profiles. Addressing the second part of the **Sub-RQ1a "What is the current state-of-the-art in 2D and 3D Land Administration around the world, as documented by global reports and reported by countries",** the analysis of priorities and challenges for 3D LAS worldwide, as revealed in the responses to the 4th FIG Questionnaire, underscores the varying readiness and focus of countries in their transition toward 3D systems. Legal, organisational, and technical challenges emerge as common axes across jurisdictions. Many countries emphasise the need for legal reforms to accommodate 3D-specific complexities, such as vertical property rights and multilayered ownership. Organisational challenges include capacity building, stakeholder engagement, and fostering institutional alignment, while technical priorities focus on data interoperability, advanced tools such as BIM, and adopting technologies like VR and AR. *These priorities reflect the diverse needs of countries at different stages of LAS maturity, from foundational development in emerging systems to fine-tuning in advanced systems.* This diversity also reveals the importance of tailoring approaches to regional contexts, legal structures, and technological capabilities.

Following this analysis on global level with regards to the advancements of 3D LASs, the chapter continues with the *analysis of existing LADM-based country profiles* highlighted shared characteristics and distinct differences in how countries approach profile development. *Five critical criteria are identified: profile scope, stakeholder involvement, the status of existing LAS, the stage of profile development, and considerations for 3D LAS*. Countries with advanced LAS, such as Switzerland and The Netherlands, focus on refining existing systems and integrating modern functionalities. In contrast, countries like Nepal and Kenya concentrate on foundational challenges, such as establishing legal frameworks and addressing capacity gaps. The analysis also revealed the importance of collaborative approaches involving government, academia and private stakeholders, which enhance the theoretical robustness and practical applicability of profiles. These lessons learnt extend beyond the characteristics themselves, addressing aspects like the validation of developed profiles, training of relevant stakeholders, and dissemination strategies. The iterative refinement of profiles, driven by stakeholder feedback and institutional engagement, demonstrates the dynamic and adaptive nature of LADM implementations. **Building on these insights, a structured methodology for creating LADM-based country profiles is developed**.

This methodology emphasises iterative processes across three phases: scope definition, profile creation, and testing. The first phase involves defining the scope of the profile and identifying stakeholders, ensuring alignment with national priorities and existing LAS. The second phase focuses on the conceptual design using UML models, incorporating LADM concepts while allowing for local adaptations. The third phase translates these conceptual models into technical implementations, including database schemas and real-world testing with sample datasets. The iterative nature of this methodology ensures continuous improvement and adaptation to evolving needs and technologies, such as 3D visualisation and enhanced querying capabilities. It is designed to be flexible, accommodating both LADM Editions I and II and addressing diverse legal, institutional, and technical contexts.

The chapter also highlights the need for harmonisation in legal, organisational, and technical aspects to facilitate the transition towards 3D LAS. Harmonisation is essential to achieve interoperability, facilitate cross-border collaboration, and enable the integration of diverse data sources within and across jurisdictions. However, harmonisation must be approached at different levels, recognising the divergence in national legal frameworks, administrative structures, and technological capabilities.

The need for harmonisation in 3D LAS implementation arises from the necessity to achieve interoperability, facilitate cross-border collaboration, and integrate diverse data sources. However, harmonisation must be approached at different levels while respecting national legal frameworks, administrative structures, and technological capabilities. *Legal harmonisation* is challenging due to the sovereignty of national property laws, as seen in the EU, where standardisation in LA is deliberately avoided. Instead, a common reference model like LADM provides a structured framework for aligning different national systems without imposing uniform regulations. In contrast, *technical harmonisation* is more feasible and beneficial, as shared data models, encoding formats, and interoperability protocols enhance system integration and data exchange. Open standards such as LADM and OGC-compliant services enable national flexibility while maintaining compatibility with regional and global initiatives. *Organisational harmonisation* focuses on aligning institutional roles and workflows, ensuring better coordination between land administration agencies, which often operate with fragmented responsibilities.

8 Validation of the Proposed Developments

[Sub-RQ7] **How can the applicability and functionality of the survey model for LADM Part 2- Land Registration be validated a) at conceptual level; b) at a 3D web-based platform and c) how the applicability of the reference cadastral survey workflow can be validated?**

This chapter is partially based on the following publications:
Kalogianni, E., *van Oosterom, P.J.M., Schmitz, M., Capua, R., Verbree, E., Dimopoulou, E., Gruler, H.C., Stubkjær, E., Neudiens, I., Morales, J., Lemmen, C.H.J. (2023). Galileo High Accuracy Services support through ISO 19152 LADM Edition II. In Proceedings: FIG WW 2023, ISBN: 978-87-93914-07-0.*
Kalogianni, E., *Dimopoulou, E., Gruler, H.C., Stubkjær, E., Morales, J., Lemmen, C.H.J., van Oosterom, P.J.M. (2024). Refining the survey model of the LADM ISO 19152–2: Land registration. Land Use Policy, 141, 107125. doi: https://doi.org/10.1016/j.landusepol.2024.107125.*
Kalogianni, E., *Dimopoulou, E., Gruler, H.C., Stubkjær, E., Lemmen, C.H.J., van Oosterom, P.J.M. (2021b). Developing the refined survey model for the LADM revision supporting interoperability with LandInfra. In Proceedings: FIG Working Week 2021, pp. 27, part of ISBN: 978-87-92853-65-3.*

ABSTRACT This chapter presents the validation of the LADM Part 2 survey model through real-world use cases and prototype implementation, aiming to assess its applicability and identify necessary refinement of the proposed models, as described in section 6. Two pilot studies have been conducted in Germany (North Rhine-Westphalia) and Estonia (Tallinn) (in the context of the H2020 GISCAD-OV project) demonstrating the model's applicability across different regulatory and geographic contexts (section 8.1). These case studies validate the refined survey model by ensuring compliance with local cadastral standards while integrating GNSS-based surveying methods, including Galileo HAS. The validation process involves field data collection, including parcel boundary surveys, assessment of GNSS accuracy and data processing for cadastral registration. The study highlights the flexibility of the LADM survey model in accommodating diverse national requirements. Additionally, instance-level diagrams are developed to validate the survey model conceptually, demonstrating how theoretical constructs integrate into real-world cadastral workflows. Moreover, the

chapter discusses the validation of the reference cadastral workflows in Denmark, Greece, and Colombia, showcasing its adaptability to different levels of LAS maturity (section 8.2).
To further validate the model's functionality in a digital environment, a 3D WebGIS prototype is developed, integrating BIM, survey and cadastral data within a web-based spatial interface (section 8.3). This prototype, built using CesiumJS for 3D visualisation and a PostgreSQL/ PostGIS database, allows users to query, visualise, and interact with LA data, demonstrating how LADM-compliant survey models can enhance decision-making. The prototype was tested using the Kaja Cultural Centre IFC model in Tallinn, linking spatial, administrative, and survey data, including GNSS observations.
Collectively, these validations confirm the survey model's robustness, interoperability, and practical applicability across various cadastral environments, ensuring its alignment with international standards and facilitating its broader adoption. The chapter concludes with a summary of the evaluation results of these three aspects (section 8.4).

8.1 Use cases and instance level diagrams of the LADM Part 2 survey model

To validate the proposed developments of the Survey Package and the Surveying and Representation sub-package of LADM Edition II (section 6.3), real-world data from pilot campaigns conducted within the context of the H2020 GISCAD-OV project are used. This section presents two pilot studies that demonstrate the validation of the conceptual model.

The first pilot study took place in Germany (North Rhine-Westphalia) from 19 to 22 September 2022. It focused on testing the applicability and functionality of the conceptual model within an urban setup. The second pilot involved a site in Estonia, including a building, surveyed at the beginning of December 2022. Practical insights into the implementation and testing of the LADM Edition II extensions are provided, showcasing their capability to address diverse LA scenarios in varying geographic and contextual settings.

The field data collection process for both pilot projects was conducted in adherence with local regulations and the required accuracy standards. A systematic approach was followed to ensure compliance and precision, comprising several key steps. The process began with the survey team's arrival at the test site. Formal authorisation was then obtained from property owners and neighbours This allowance was needed for both adhering to local cadastral procedures as well as for simulating property surveys under the GISCAD-OV project.

Subsequently, a reconnaissance and evaluation of the test site was carried out. Surveyors commenced by locating existing ground marks using available cadastral information. Objects relevant to the cadastral survey, such as geodetic network benchmarks, reference points, border points, buildings, and structures, were then inspected. The accuracy of control ground marks was assessed, and decisions were made regarding their suitability. If marks were found to be outside the accepted tolerance, new ground points were established.

For cases involving new parcels or subdivisions, new ground points were set up where required. Based on the site conditions, the most suitable survey method was selected, including GNSS, total stations, hybrid approaches, orthophotos, or other methods and combinations. Finally, surveys and geodetic measurements were performed in compliance with cadastral measurement standards and local regulations.

The GNSS data requirements for property surveying tasks in Estonia and Germany (specifically North Rhine-Westphalia) show clear differences in regulatory frameworks and technical parameters. Both approaches set minimum standards for data accuracy and compliance in cadastral surveys. This analysis reflects the diversity in GNSS cadastral surveying practices and their alignment with local regulations and international standards.

In Estonia, the GNSS survey report must include basic information critical for property surveying tasks. These include the survey point number, X and Y coordinates, horizontal accuracy estimates or the standard error of the mean, and the satellite positioning indicator (PDOP). The report also requires documentation of the number of satellites observed at the time of the survey, details of the initial solution, and the measurement point code along with its meaning if surveyor-specific codes are used. Additional details such as the boundary point number and compliance with the legal framework are mandatory. These requirements provide a straightforward yet robust framework to facilitate consistency and reliability in GNSS-based property surveys.

In Germany (North Rhine-Westphalia), GNSS data requirements are notably more detailed and technically advanced, mandating comprehensive documentation of various data to ensure high precision and reliability in cadastral surveying.

The survey report must detail the type of GNSS used, the number of satellites observed per system, the utilised frequencies, and the cut-off elevation angle. Additionally, it includes specifications such as the receiver and antenna type/serial number, date and time of initialisation, antenna height, point identifier, and feature type identification. Accuracy metrics, including GDOP, derived from PDOP and TDOP, RMS values, and UTM coordinates (E, N, and ellipsoidal height), must also be recorded. To enhance reliability, at least two independent point observations with different satellite constellations are required. Further, strict limits on standard deviations and deviations between individual measurements are enforced, ensuring data accuracy and compliance with regulatory standards.

The North Rhine-Westphalian specifications go beyond simple GNSS data collection to include parameters such as the number of measurement epochs (at least 10 with an interval of 1 second), quality assessments for individual measurements, and specific limits for deviations in position and height coordinates. The regulatory framework is detailed in the administrative regulation of NRW that provides detailed guidelines for conducting surveys and documenting the collected geospatial data (Erhebungserlass (ErhE), particularly in Annexes 8b)[30].

This comparison of GNSS data requirements in Estonia and Germany (NRW) underscores the diversity in cadastral survey practices. Estonia prioritises simplicity and efficiency within a standardised framework, facilitating compliance and accessibility. In contrast, Germany (NRW) prioritises technical precision and redundancy measures to guarantee high data accuracy.

This variation reflects the balance between regulatory precision and practical applicability in LASs. The LADM Edition II Part 2 survey model effectively accommodates both approaches, providing a standardised, yet flexible structure that supports diverse national implementations, as discussed in the following sub-sections.

For each use case, instance-level diagrams have been created and presented in sub-sections 8.1.1 and 8.1.2, demonstrating the applicability of the refined survey model. Instance-level diagrams serve as essential validation tools, illustrating how abstract concepts and associations from the conceptual model can be translated into real-world scenarios. By bridging theory and practice, instance-level diagrams not only confirm the feasibility of the survey model but also facilitate the identification of any gaps at the initially proposed model. This iterative validation process ensures continuous improvement and refinement, strengthening the model's robustness and adaptability for various cadastral survey contexts.

30 https://recht.nrw.de/lmi/owa/br_bes_text?anw_nr=1&gld_nr=7&ugl_nr=71342&bes_id=37728

8.1.1 Use case in Olpe, Germany

In the German use case, the cadastral survey was conducted in a land parcel located in the grasslands near Olpe, North Rhine-Westphalia. Two sets of GNSS data were collected, enabling the evaluation of equipment and software tools supporting Galileo HAS, which were still under development in 2022. The field data were analysed to assess precision across different sets of observations and to evaluate the relative accuracy of Galileo HAS in cadastral applications.

Survey conditions were generally favourable, with an open sky and minimal survey obstructions, ensuring optimal GNSS signal reception. However, initial measurements were taken near a road with canopy coverage, introducing some challenges that impact accuracy. This variation in survey conditions provided insights into the performance of Galileo HAS under different environmental constraints, contributing to a broader understanding of its applicability in rural cadastral surveying. At the survey, also TUDelft MSc Geomatics students (Figure 8.1) have participated, using appropriate equipment for data collection (van Capel et al., 2023).

FIG. 8.1 Surveying the pilot parcel in Olpe, Germany.

In areas with limited satellite availability, points were measured exclusively using the PPP-RTK method. In other locations, measurements were taken using both PPP-RTK and Galileo HAS methods, allowing for a comparative evaluation of accuracy and reliability.

The datasets were acquired using a GPS-Galileo multi-constellation system, which included nine GPS satellites and six Galileo satellites, ensuring comprehensive coverage. This dual-method approach provided insights into the capabilities of Galileo HAS and its effectiveness in cadastral surveying across varying environmental conditions.

The field-collected GNSS data underwent processing and analysis, supplemented by additional datasets to enhance accuracy and verification. A Digital Terrain Model (DTM) from Olpe, provided by the Geobasis of North Rhine-Westphalia[31] (under the German governmental district of Cologne). Additionally, a 3D Building Model for Olpe, in Level of Detail 2 (LoD2), was obtained from Geobasis NRW in OGC CityGML format. This dataset included the tile set covering the surveyed urban parcel, offering contextual insights. The integration of these datasets improved the precision and reliability of the cadastral survey, ensuring a more realistic representation of the surveyed area and its surroundings.

The instance level diagram of this use case is presented in Figure 8.2.

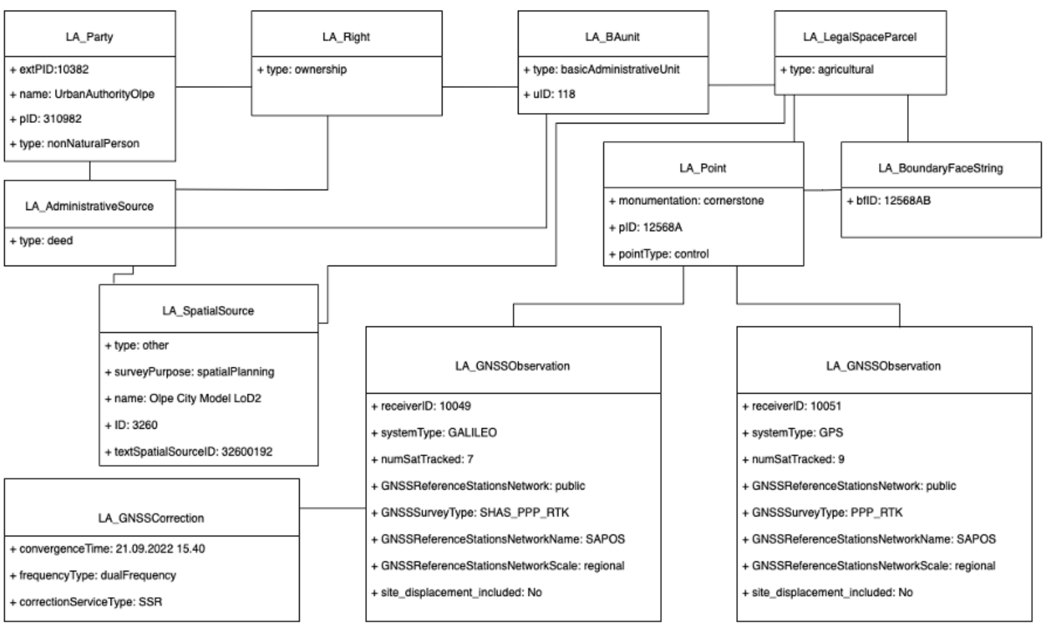

FIG. 8.2 Instance level diagram for the pilot parcel in Olpe, Germany showcasing datasets acquired using Galileo HAS

31 https://www.bezreg-koeln.nrw.de/geobasis-nrw

The values of the various classes related to party and administrative data were easy to complete and data were retrieved from the administrative source.

To efficiently populate the attributes of the LA_GNSSObservation class, it is essential that the surveyor records key information during fieldwork, such as the number and type of satellites tracked. Complementary details, including the GNSS reference station network used, shall be documented during post-processing in the office. While all information needed to complete the instance level diagram, can ultimately be recorded, it is important to note that such data is not always automatically captured by GNSS equipment and may require manual documentation and integration.

8.1.2 Use case in Tallinn, Estonia

The second pilot, conducted in Tallinn, Estonia, also as part of the H2020 GISCAD-OV project, followed the same GNSS and Galileo HAS measurement approaches as the German pilot. The survey focused on the plot containing the Cultural Centre building, integrating field-collected GNSS data with an as-built BIM model provided by the Municipality of Tallinn in IFC format (Figure 8.3 and Figure 8.4). This model was integrated with Galileo-only measurements to reconstruct the plot boundary, utilising Galileo HAS corrections to enhance precision.

The instance-level diagram (Figure 8.5) serves as a validation tool for the proposed survey model, demonstrating its capability to integrate both administrative and spatial data sources while facilitating the reuse of design-phase information—in this case the ‘asBuilt’ IFC file. This approach underscores the importance of combining multiple data sources within a lifecycle-oriented framework, enhancing the accuracy and efficiency of cadastral surveys and showcasing the potential of modern geospatial technologies in LA.

FIG. 8.3 Pilot execution at the plot where the Kaja cultural centre of Tallinn, Estonia is located

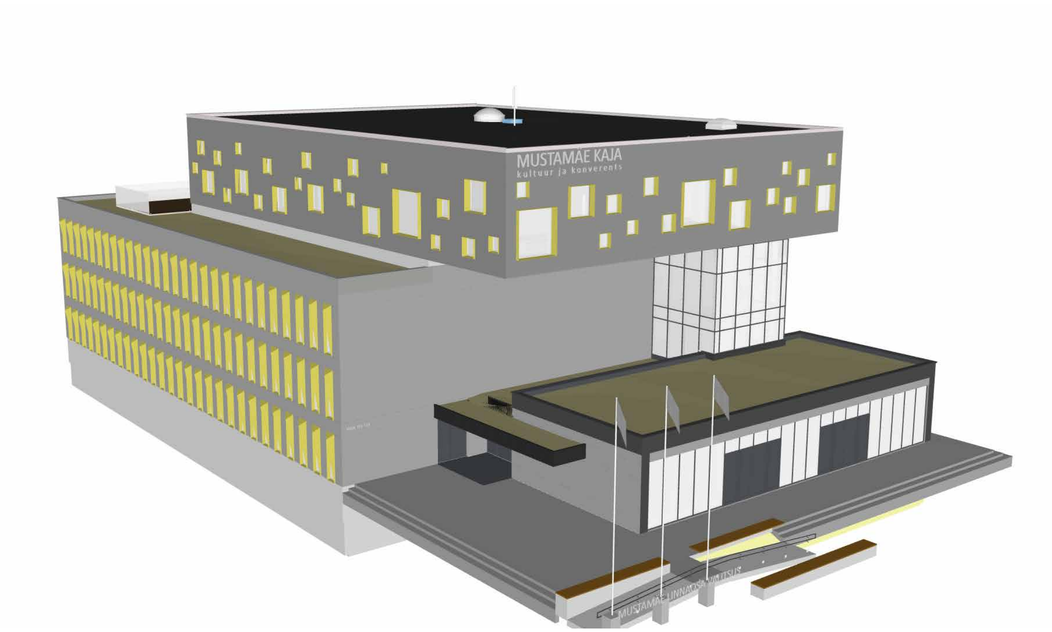

FIG. 8.4 The BIM file for the Kaja Cultural Centre of Tallinn, Estonia

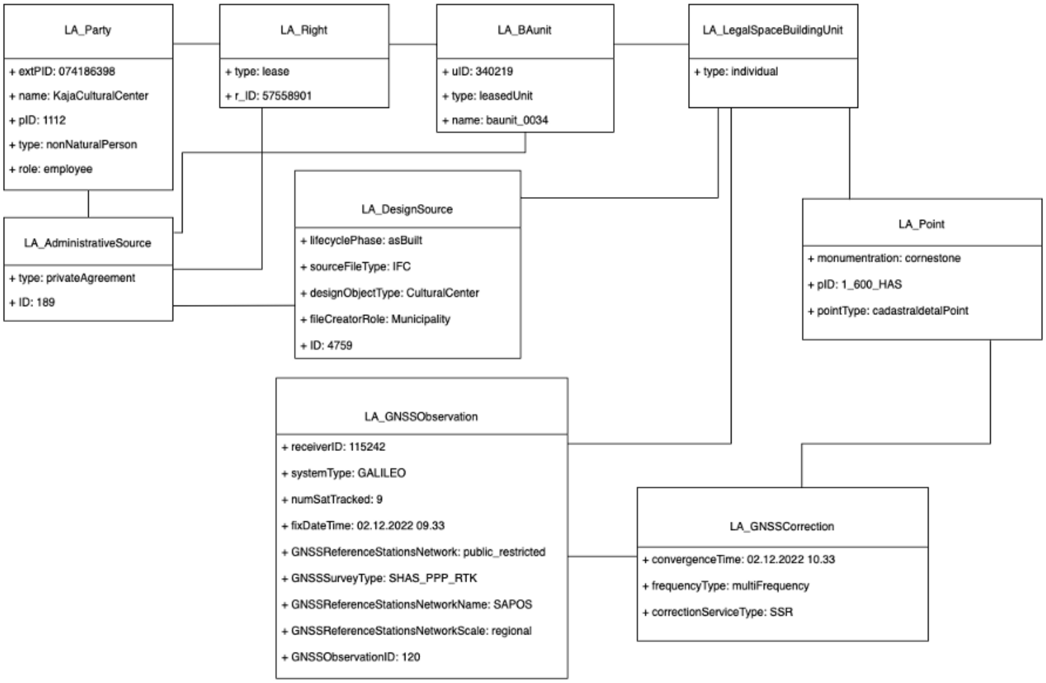

FIG. 8.5 Instance level diagram for the pilot plot of the Kaja Cultural Centre of Tallinn, Estonia

For the creation of the instance-level diagrams the refined survey model, as presented in section 6.3, has been used and it validates that the proposed survey model meets the requirements of cadastral surveying while effectively supporting GNSS corrections. Data collected from Germany and Estonia, each with distinct legal frameworks and established LAS, confirm the conceptual model's applicability in different cadastral contexts. Those use cases explicitly demonstrate that the refined survey model, with all necessary attributes, whether measured or derived, is adequately modelled and well aligned to real-world survey requirements.

A key observation is that certain GNSS correction-related attributes could not be directly obtained from GNSS receivers but required post-processing at the office. However, this limitation does not impact the model's functionality or completeness. As Galileo HAS continues to evolve, it is anticipated that software and equipment providers will enhance their products, enabling the direct derivation of these attributes. Such advancements will further increase the efficiency and applicability of the model in cadastral surveying, reinforcing its role in modern land administration workflows.

8.2 Implementation of reference cadastral survey workflow

The reference cadastral survey workflow, based on the LADM survey model and detailed in section 6.4, was validated through practical implementations in Denmark, Greece, and Colombia—each country representing varying levels of LAS maturity. This process highlighted the workflow’s flexibility and adaptability to diverse legal, institutional, and technical environments.

The creation of instance-level diagrams played a crucial role in refining the workflow, allowing for iterative improvements in response to observed inconsistencies. For example, feedback from the Danish case led to the inclusion of a tolerance validation step during the professional spatial data collection phase. Similarly, the Colombian use case introduced the notion of “socialisation” and integrated training as an initial step towards participatory, community-based spatial data collection under professional supervision. All these, have contributed to the final version of the workflow, as presented in section 6.4.

In Denmark, where a well-established LAS exists, the workflow demonstrates its ability to integrate seamlessly with a mature cadastral system. The Danish LAS benefits from robust institutional frameworks, clear legal procedures, and high-quality cadastral data. The LADM survey model complements this environment by enhancing functionality for validations in consistency in data collection and registration. Its focus on precision and established standards aligns well with Denmark’s advanced system, streamlining processes and ensuring compliance with national regulations.

In Greece, where the LAS is still under development, the LADM survey model proves to be effective in providing a structured and systematic approach. The cadastral system of Greece is transitioning and this process can be supported by this workflow’s emphasis on data integration, accuracy, and validation. This workflow ensures that cadastral records are consistently updated in alignment with legal and technical requirements. Its modularity also allows Greece to adapt the workflow to different levels of system readiness, accommodating ongoing developments.

Finally, in Colombia, a country with a post-conflict situation and a rapidly developing LAS, the workflow demonstrates its ability to function in complex and challenging environments. Colombia’s test of participatory mapping and crowdsourcing techniques is a key innovation to address the lack of complete formal cadastral records and the need for community engagement. The LADM survey model accommodates these approaches by integrating grassroots data collection with professional and institutional processes. Its ability to handle diverse sources of data—ranging from crowdsourced information to formal cadastral records—facilitate the creation of reliable and inclusive land records -as tested in the country. This flexibility is particularly valuable in contexts where land tenure is complex, and rapid system development is essential for social and economic stability.

In these three countries, the existing cadastral survey workflows (in Colombia under test) were studied and analysed by Kalogianni et al. (2021b). These workflows are then aligned with a reference workflow (sub-sections 8.2.1, 8.2.2 and 8.2.3), and therefore the consistency of the workflow can be assessed. This process also allows for the identification of potential issues related to the components of the LADM survey model, offering insights into its applicability and areas for improvement.

8.2.1 Implementation of the reference cadastral survey workflow for parcel subdivisions in Denmark

The cadastral organisation in Denmark and the subdivision process is outlined in the report "Property Formation in the Nordic Countries" (Kort og Matrikelstyrelsen, 2006). Figure 8.6, illustrates the surveying component of the subdivision process, based on the reference cadastral workflow of LADM Edition II.

Cadastral surveying in Denmark follows a structured workflow, fully digital, beginning within the private surveyor requesting and retrieving existing cadastral data—such as cadastral identifiers and archived measurements of boundaries — which are reviewed alongside the owner's request to develop a survey design. During fieldwork, updated spatial data is collected by referencing control points and cadastral evidence (e.g., boundary marks, house corners, or other well-defined spatial features). Boundary points are then marked, and the spatial data collection is completed.

Back in the office, the cadastral changes are documented and validated against the applicable requirements. The focus remains on surveying, without incorporating aspects such as party confirmations, spatial planning, environmental regulations, or consultations with municipalities. Finally, the completed case is submitted to the Danish Geodata Agency, which reviews the submission to ensure compliance with cadastral regulations. Upon verification, the agency approves the proposed changes, ensuring that boundary definitions and spatial data collection are conducted with high precision, maintaining the integrity of the Danish cadastral system.

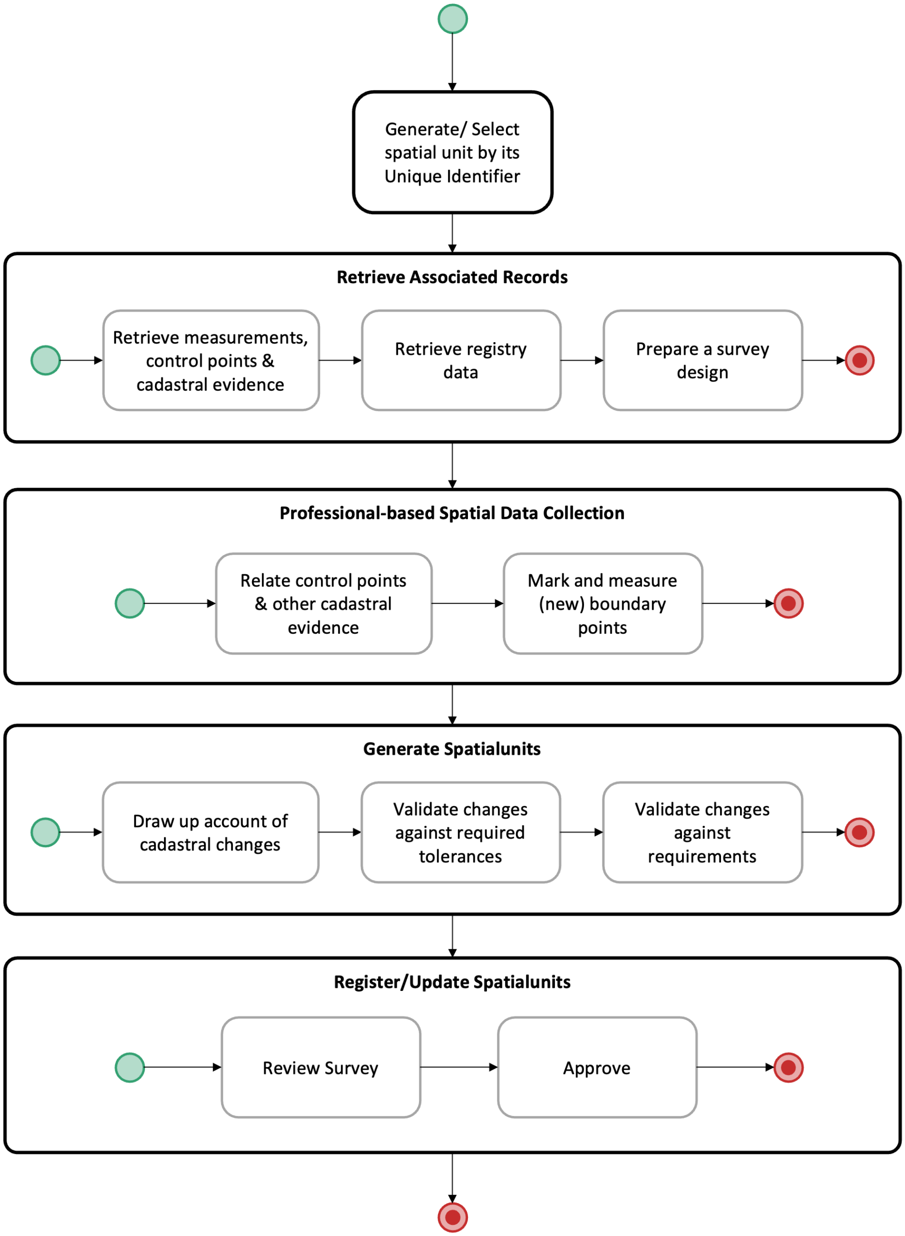

FIG. 8.6 Implementation of the reference cadastral survey workflow for Denmark

8.2.2 Implementation regarding the cadastral survey workflow for parcel subdivisions in Greece

The Hellenic Cadastre (HC) – Ktimatologio is a property-based system that records and maintains both the technical (location and boundaries) and legal information of real properties, all linked via a Unique National Cadastre Code Number (KAEK). When a registrable event, such as a merger (where a new spatial unit is formed) or subdivision, results in a geometric change, the cadastral surveying process is carried out by a private, licensed surveyor. This process involves collaboration with the Hellenic Cadastre, who provide the necessary information and guidance to facilitate compliance with local requirements and regulations. The workflow is illustrated in Figure 8.7.

The first step in the process involves selecting the cadastral number(s) of the parcels or areas undergoing change. By referencing this number, the survey workflow can be tailored to the specific spatial unit and its corresponding cadastral records, ensuring adherence to local procedures. This process is digital, through a web-based system.

The surveyor must then obtain the existing cadastral survey diagram of the spatial unit from the cadastral authorities through a web-based system. This includes gathering any additional required documents, such as cadastral maps, historical records, and deeds. Upon request, the cadastral office issues the cadastral survey diagram, which contains detailed (spatial) information about the parcel. The first page of the diagram shows the parcel, scaled to size, with the area according to cadastral data and the value of the linear distortion in EGSA87 (the national reference system). The second page provides a table of coordinates and the corresponding spatial unit. Information about control points (trigonometric and urban network points) required for the survey is made accessible through the official website and the electronic services portal.

Subsequently, the surveyor conducts spatial data collection in the field. This involves taking measurements and locating existing boundaries, landmarks, and physical features using professional surveying equipment. Based on the fieldwork results, new boundaries are established in the field, ensuring compliance with zoning regulations. The surveyor then prepares an updated cadastral diagram that reflects the geometric changes of the spatial unit. Depending on the type of change, different updates will be included in the cadastral diagram.

The final step involves submitting the updated diagram to the HC system, along with the application for registering the changes and the corresponding corrections or updates of the geometric data. HC then undertakes the last step of the application verification and updating the cadastral records and map.

This workflow ensures that all cadastral changes are accurately recorded, maintaining the integrity and accuracy of the Hellenic Cadastre system.

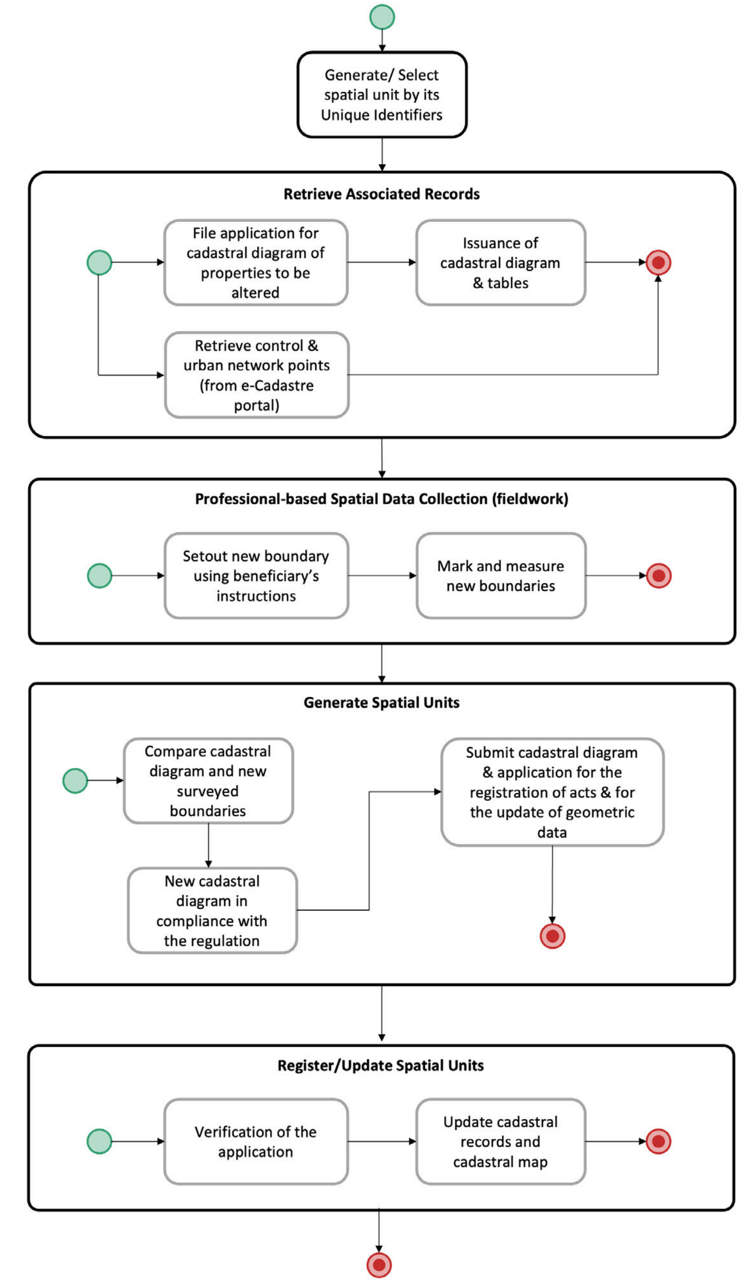

FIG. 8.7 Implementation of the reference cadastral survey workflow for Greece

8.2.3 Implementation regarding the cadastral survey workflow for initial registration in Colombia

This sub-section illustrates a case study from Colombia, where participatory mapping has been applied and tested, as detailed by Morales et al. (2021). The Colombian approach to land rights recordation in this test operates on two levels. Initially, a group of national agencies—including Land, Mapping, and Registry authorities—identify the areas to be surveyed, assigning unique use case identifiers. This is followed by local socialisation and training events designed to engage and educate stakeholders about the process.

The main objective of this participatory mapping approach is to document unspecified rights, referred to as an "*consideration*," along with the identity of the person holding the tenure relationship and the land parcel for which the consideration is valid. The process involves grassroots surveyors, land professionals, university staff, and employees from the national agencies, all working closely with leaders of the local community or communities (as depicted in Figure 8.8). Parallel to these activities, the agency group collects and provides relevant data sources, including existing cadastral records, orthophotos, and/or satellite images.

The mapping process begins with claimants identifying the location and approximate area of their land interests during a planning phase using a base map, such as an orthophoto or high-resolution satellite image. Grassroots surveyors then accompany claimants to the field, where they measure land boundaries in terms of VertexPoints and AnchorPoints, while non-private features like rivers or roads are documented as ReferenceObjects (Morales et al., 2021). Evidence supporting existing rights, such as documents and photographs, is also recorded.

The surveyed data is processed into topologically correct parcel representations. These representations are analysed to classify the various types of rights and are compared with existing government registers where applicable. The processed results are then presented to the community during a public forum for approval. Community members provide validation by signing agreements, indicating consensus among the involved parties. Approved parcel data is subsequently submitted to national agencies for further processing.

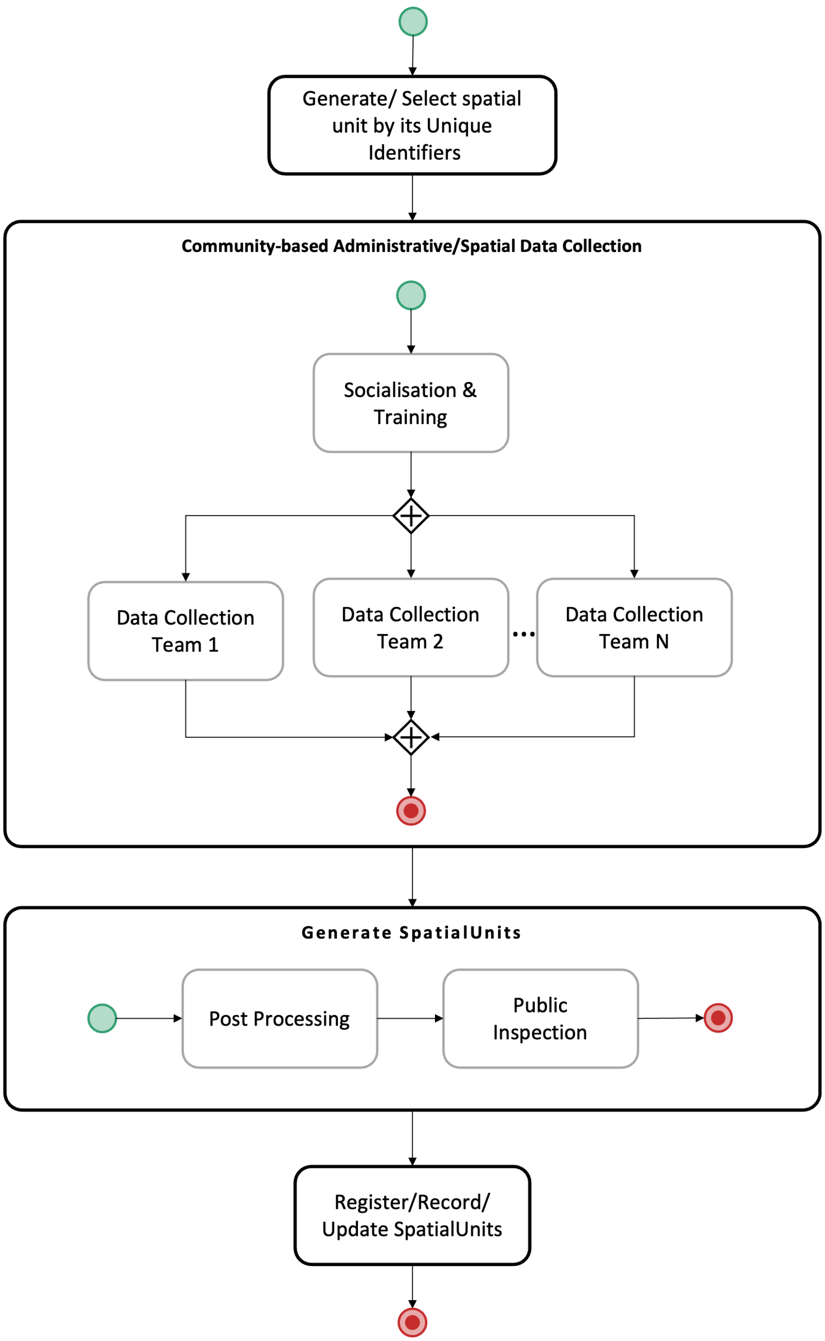

FIG. 8.8 Implementation of the reference cadastral survey workflow for Colombia

The national agencies review and analyse the data to generate official documentation for the various rights holders. In some instances, rights can be immediately formalised, resulting in land titles. For other rights categories, additional procedures are required, but they may also lead to formal titles. The sequence of activities is iterative and open-ended to address other not registered, allowing for flexibility in addressing various types of land rights and formalisation pathways. This participatory approach facilitates transparency, community involvement, and alignment with local and national requirements.

The Colombian case differs from those of Greece and Denmark, and as such, the workflows are not directly comparable. Nevertheless, the generic reference workflow demonstrates sufficient flexibility to accommodate these variations. It provides a common foundation that can be adapted to reflect specific local requirements, allowing each jurisdiction to model and enrich the workflow with context-specific stages and procedures.

8.3 3D Web-based prototype implementation

To further assess the survey model's functionality in a digital environment, a 3D web-server, DBMS and WebGIS prototype was developed, integrating BIM and LA data within a web-based spatial interface. This section presents the design, development, and implementation of the 3D WebGIS prototype. It provides a web-based interface for visualising, querying, and managing BIM data together with LADM data for 3D LA purposes and allows for interactive exploration of LA and building-related information, enhancing spatial data interoperability and decision-making. The prototype is available at: http://159.223.219.149.

The system architecture of the 3D web prototype for LA is designed to facilitate seamless integration of BIM and LA data within a spatially enabled WebGIS environment. It follows a client-server architecture comprising a frontend, backend, and database, ensuring efficient data retrieval, processing, and visualisation. The frontend is built using CesiumJS, a powerful JavaScript library for 3D geospatial visualisation, which enables users to interact with 3D tilesets and explore LA data. It communicates with the backend API, which is developed in Node.js with Express, handling data requests, authentication, and spatial queries.[32] The database layer, implemented in PostgreSQL with PostGIS support, stores and manages spatial data, including IFC elements, party data and administrative information, ensuring high-performance querying and spatial indexing for efficient data retrieval.

The 3D web prototype's database is structured using PostgreSQL with PostGIS to support efficient storage and management of both spatial and non-spatial data. The core tables consist of those derived from IFC models and others containing LADM-related information, as shown in Table 8.1 and Figure 8.10. In addition to these two main categories, supplementary tables have been implemented to establish associations between BIM and LADM entities and to model many-to-many relationships, ensuring flexible data integration and interoperability within the system.

32 The backend includes endpoints such as /api/ifc/properties/:guid (fetching properties from kaja_ifc_properties and materials from kaja_ifc_materials), and /api/la/building/:ifc_id (linking IFC elements to legal rights via la_right_baunit).

TABLE 8.1 Overview of DBMS tables

	DBMS Table	DBMS Table Description
BIM-related tables	kaja_ifc	stores IFC elements along with their names, descriptions, and GUIDs
	kaja_ifc_properties	manages IFC element properties grouped by property sets
	kaja_ifc_materials	links materials to their respective IFC elements
	kaja_ifc_relationships	stores element connections
	tiles	includes 3D geometry binaries
	tileset_metadata	includes tileset configurations
LADM-related tables	la_party	stores information about party entities
	la_rrr	Includes the rights, restrictions and responsibilities
	la_right	includes data about rights
	la_baunit	contains information about basic administrative units to which RRRs are attached
	la_administrativesource	contains information about legal sources
	la_spatialsource	includes the spatial sources
	la_designsource	includes the design sources
	la_spatialunit	includes information about the spatial unit
	la_legalspacebuildingunit	contains the legal parts of building units
	la_gnssobservation	includes information about the GNSS data from the survey source
	la_gnsscorrection	includes information about the corrections of GNSS observations

The database schema is structured to support efficient querying of spatial relationships and attributes, leveraging indexing strategies and foreign key constraints for consistency to enhance database's performance. PostgreSQL's dynamic data handling capabilities manage property sets and material details, while PostGIS enables advanced spatial functionalities. For instance, GiST-based spatial indexing for fast data retrieval, geospatial queries for distance and intersection calculations, and transformation tools for rendering spatial data in web-friendly formats are supported. This approach ensures seamless integration of IFC data with LADM-compliant LA information, creating a solid foundation for managing and visualising 3D spatial units.

Figure 8.9 presents an overview of the DBMS tables and their attributes.

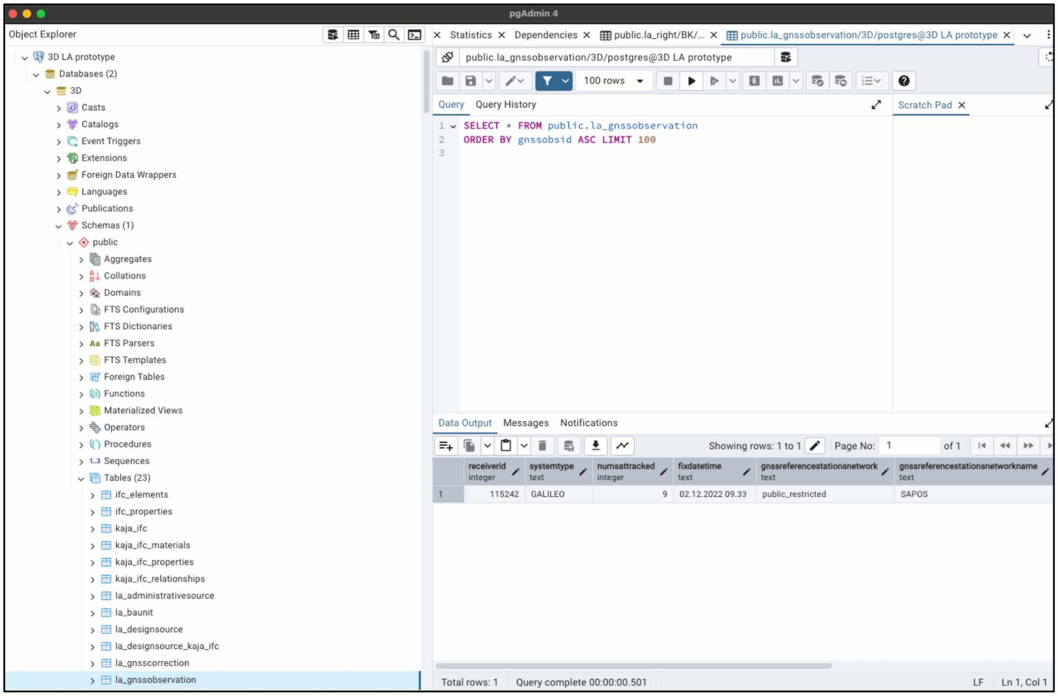

FIG. 8.9 Tables and attributes of the database for the 3D web prototype

The system's data flow begins with the frontend issuing requests to the backend API. These requests are processed by the server, which subsequently queries the PostgreSQL database and returns structured JSON responses. The backend provides RESTful endpoints to retrieve various types of data, including 3D (stored in the tiles table, with attributes such as tile_path and tile_content), IFC elements (from tables like kaja_ifc, which include fields such as guid, ifc_class, and room_bounding), and land administration data aligned with LADM (e.g., party information from la_party and rights from la_right). Once the data is received, the frontend uses CesiumJS to render and dynamically update the 3D visualisation, allowing users to interact with and explore the data interactively d. The backend also incorporates CORS (Cross-Origin Resource Sharing) handling to ensure secure access across different domains and serves necessary static files for rendering and interface functionality. In the prototype, enabling CORS allows the CesiumJS frontend to request tilesets, IFC elements, and LADM data from the backend API without being blocked by the browser's same-origin policy, while still enforcing security through controlled access.

The tiles and tileset_metadata tables store content from the two components of the 3D Tiles format—tiles contains data from the .b3Dm files, while tileset_metadata holds information from the tileset.json files. A Python script is used to import this data into the database. Together, these tables manage 3D tile content and metadata, supporting efficient rendering and interaction within the web-based interface.

As input data, the IFC model of Kaja Cultural Centre of Tallinn, Estonia, as well as the survey data from the the same pilot, that was also used for the instance level diagram to validate the survey model at a conceptual level (section 8.1) is used. This model populates the tables kaja_ifc and kaja_ifc_properties. With regards to the corresponding legal and administrative information, data from the Municipality is stored in LADM tables like la_administrativesource and la_right. For the LA_GNSSObservations and LA_GNSSOcorrection classes, data from the pilot that was carried out in the context of H2020 GISCAD-OV project is stored.

The system architecture is presented in Figure 8.10:

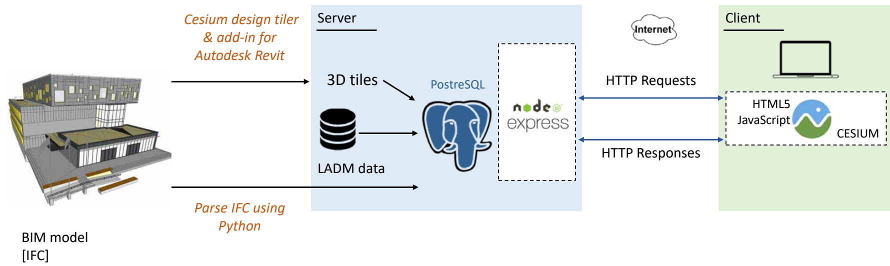

FIG. 8.10 System architecture of the 3D WebGIS prototype for 3D LA integrating BIM

The displayed information is divided into two main sections. The first section presents data extracted from the IFC model, detailing building characteristics. The second section provides LA-related information structured according to the LADM Part 2 of Edition II, outlining RRRs associated with the queried spatial unit. In the case of room ‘402’, two corresponding records are found, each linked to different parties holding RRRs for the unit (Figure 8.12). This structured approach allows users to efficiently navigate and analyse both spatial and administrative data within the prototype, demonstrating its capability to integrate BIM and LA information in a 3D environment.

The home screen of the 3D WebGIS prototype for 3D LA (Figure 8.11) visualises the IFC model of the cultural centre alongside surrounding city buildings represented in LoD2. The prototype offers two key search functionalities: querying by spatial unit name and by party name. This enables users to locate a specific spatial unit—such as a building, apartment, or room—or identify records associated with a particular party involved in a LA transaction, such as an owner or leasee. For example, searching for room '402' (which is actually an IFC space) on the fourth floor of the building triggers the system to find and highlight the corresponding 3D legal space within the visualisation interface.

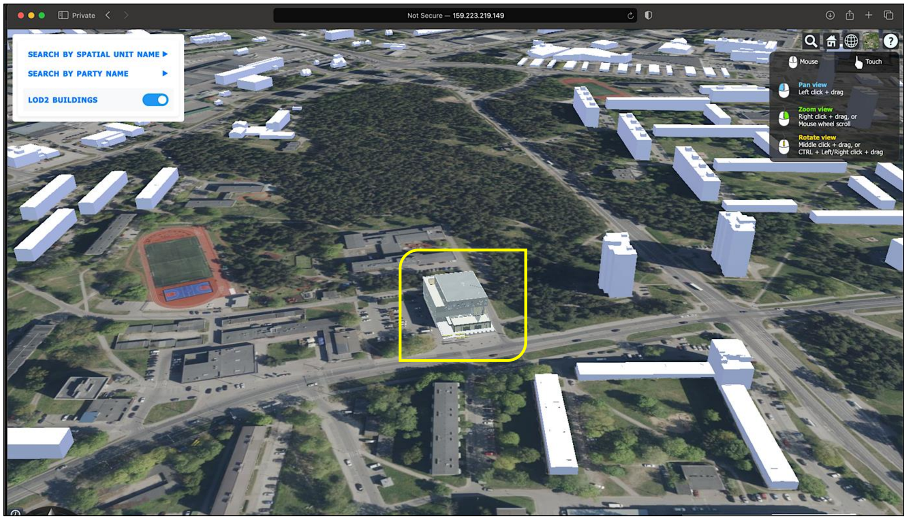

FIG. 8.11 Screenshot from the home screen of the 3D web prototype for 3D LA

A pop-up window (Figure 8.12) then displays data from two categories: the first includes information from the IFC model detailing into a selection of the most relevant spatial unit's physical attributes, while the second presents LADM-based administrative data. In this instance, two records linked to different parties are associated with room '402'. This interactive display of spatial and legal information illustrates the prototype's ability to effectively integrate BIM and LA data in a 3D digital environment.

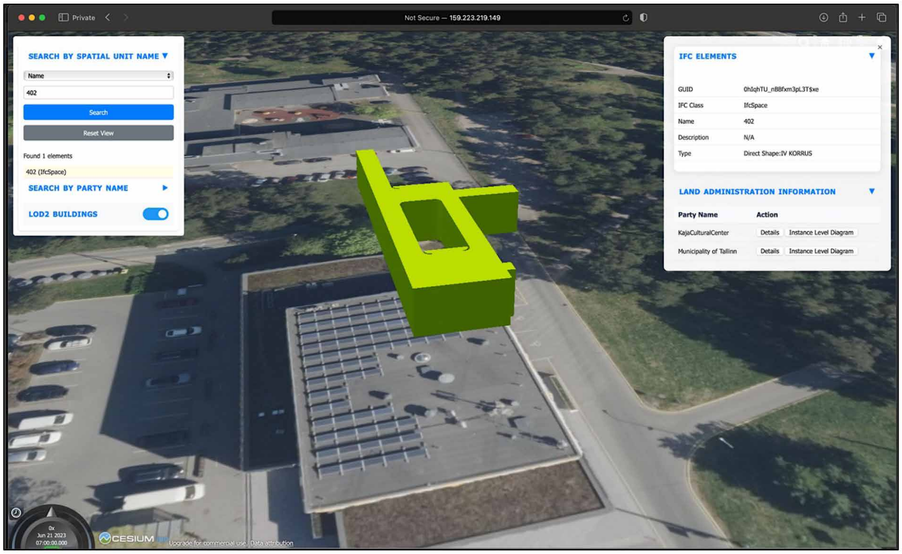

FIG. 8.12 Screenshot from results of a search by Spatial Unit name in the 3D web prototype for 3D LA

The user can then select for which one of the two parties, that have returned as result, further details shall be shown. By selecting to view more details about the Kaja Cultural Centre the window with the result of the search is further expanded.

The Cultural Centre holds a lease contract, established through a private agreement with the Municipality of Tallinn, for part of the building, that includes, among others, room ‘402’. Additionally, information about the design source, the IFC file, is represented. This is complemented by data about the GNSS observations conducted during the cadastral survey, structured according to the LADM survey model (Figure 8.14).

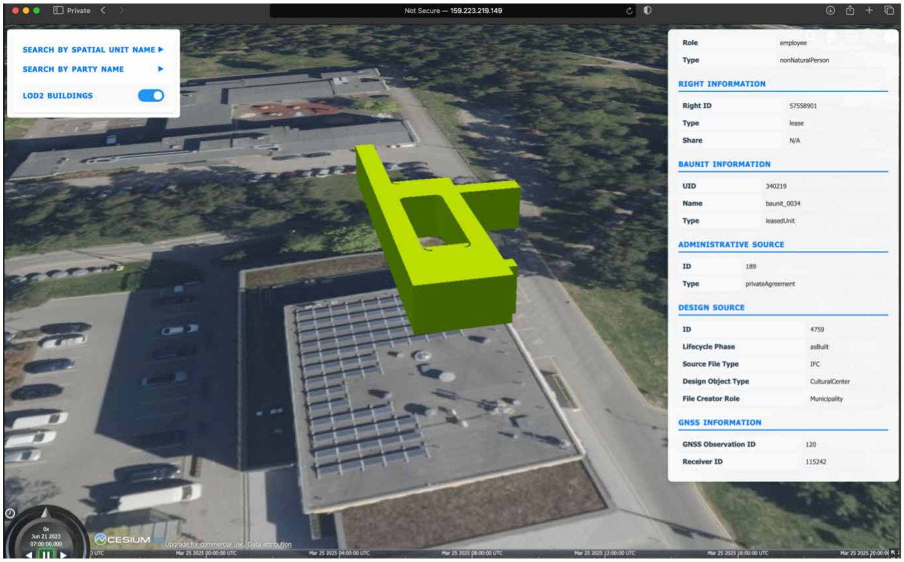

FIG. 8.13 Screenshot from the administrative information from the search result about Kaja Cultural Centre in the 3D web prototype for 3D LA

When selecting to depict further information about the RRRs attached to the spatial unit 402 and associated with Municipality of Tallinn, the pop-up window is refreshed, as presented in Figure 8.14. The Municipality of Tallinn is the owner of the building, including room ‘402’ (Figure 8.15). The information presented at the pop-up-window, includes spatial data retrieved from the IFC model, as well as legal and administrative details sourced from the LADM-related tables.

FIG. 8.14 Screenshot from the administrative information from the second search result in the 3D web prototype for 3D LA

Additionally, the prototype includes a feature that allows users to dynamically open the corresponding LADM-based instance-level diagram for the selected party (Figure 8.15). This diagram provides a structured visual representation of the relationships between the spatial unit, the involved party, and the associated RRRs, enhancing the user’s understanding of the legal and administrative context.

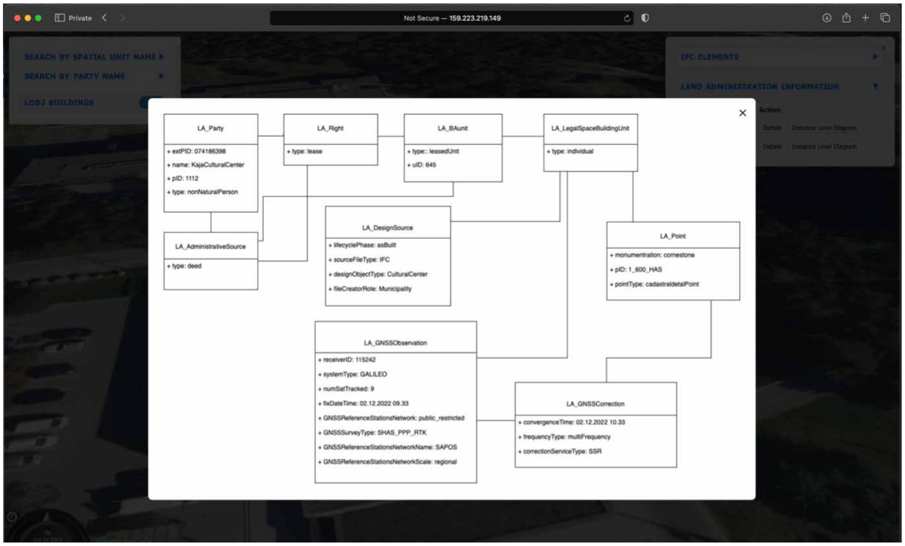

FIG. 8.15 Screenshot from the instance-level diagram of the Kaja Cultural Centre

8.4 Evaluation Results

Addressing **Sub-RQ7a "How can the applicability and functionality of the survey model for LADM Part 2- Land Registration be validated at conceptual level",** *instance level diagrams for two use cases are developed* (section 8.1). Specifically, data of two pilots that took place in Germany and Estonia (in the context of H2020 GISCAD-OV), are used to validate the conceptual model of the LADM survey model through instance-level diagrams.

Instance-level diagrams offer a tangible representation of how the LADM concepts and associations defined in the conceptual model can be applied to real-world scenarios, bridging the gap between concept and implementation. By demonstrating how the refined survey model handles complex 3D cadastral data and supports land registration and survey processes, the validation not only verifies the model's technical accuracy but also its practical applicability. Furthermore, instance-level diagrams allow for the identification of potential gaps or inconsistencies in the model, enabling (iterative) improvements and refinement. This validation contributes to the broader goal of standardisation by showcasing the robustness and adaptability of the LADM for diverse LA contexts, ensuring that it meets alignment with both international standards and specific local needs.

The creation of instance-level diagrams for the German and Estonian use cases confirms that the proposed LADM Part 2 survey model aligns with the cadastral surveying requirements outlined in section 4.2 and effectively supports GNSS corrections. Despite differences in legislative frameworks and cadastral systems, both case studies demonstrate the model's adaptability, with all required attributes—whether observed or calculated—accurately represented and their relationships properly structured. The survey model's applicability is further validated by its successful use in recording GNSS-based cadastral measurements, including those supported by Galileo HAS.

Attributes related to administrative and party data were straightforward to complete, typically retrieved from existing authoritative records. In contrast, some technical attributes—especially those linked to GNSS corrections—required proactive documentation by the surveyor in the field, such as the number of satellites. Others had to be derived in post-processing, as current GNSS receivers do not provide them automatically. While this presents a temporary challenge, it does not limit the model's effectiveness. With the increasing maturity of Galileo HAS, advancements in GNSS equipment and software are expected to automate these processes, further enhancing the model's practical utility in cadastral surveying.

The validation of the conceptual model extends beyond the afore mentioned case study implementations, to expert consultations conducted during ISO TC211 and OGC member meetings. These discussions provided critical insights from both standardization bodies and industry professionals, ensuring that the model aligns with international standards and practical applications. Within ISO TC211 meetings, representatives from national standardisation bodies contributed their expertise, refining the conceptual model. Their feedback helped shaped the model by ensuring compliance with global best practices, enhancing interoperability, and addressing technical, legal, and organisational considerations.

Additionally, *during OGC member meetings, the model's applicability within the industry was thoroughly examined.* OGC meetings bring together industry stakeholders, including technology providers, software developers, and geospatial experts and in these discussions the feasibility of implementing the model, considering the needs of private-sector and service providers was discussed. The *industry-driven feedback* was important in refining the model's technical specifications, making it more adaptable to operational workflows and emerging technologies.

To address **Sub-RQ7b “How can the applicability and functionality of the survey model for LADM Part 2- Land Registration be validated at a 3D web-based platform?”** a ***3D WebGIS prototype was developed*** (presented in section 8.3). The prototype enables interactive exploration of LA data by integrating BIM with LADM-compliant land records in a 3D web environment. The application provides an intuitive interface that allows users to query and visualise spatial units, their corresponding RRRs, as well as information derived from the LADM survey model - including both GNSS observations, and design sources such as IFC files. The structured integration of spatial and legal data into a web-based system provides a practical means of validating the survey model’s applicability, ensuring that cadastral survey records can be effectively linked to LA information in an interactive and interoperable environment.

The prototype was tested using the IFC model of the Kaja Cultural Centre in Tallinn, Estonia, alongside real-world cadastral survey data. Users can query the system by spatial unit name or by party name, retrieving both BIM-based building information and LADM-based administrative data. When searching for a spatial unit, the respective 3D legal space is highlighted, and a pop-up window displays details including IFC attributes and LAS records. The prototype also supports displaying GNSS observations and GNSS corrections stored in the database according to the LADM survey model. Furthermore, the prototype provides a dynamic link to instance-level diagrams that validate the conceptual survey model, confirming that all necessary survey attributes align with LADM Part 2 requirements of LADM Edition II. The ability to retrieve, visualise, and link survey data with spatial and administrative records in a 3D web-based environment validates the practicality and functionality of the survey model, showcasing its adaptability for real-world implementations.

One of the main challenges in developing the 3D web prototype was addressing georeferencing inconsistencies in the IFC models, particularly due to differences between IFC versions. While IFC4 supports improved spatial referencing, older versions like IFC2x3 often lack accurate geolocation data, necessitating manual adjustments to ensure alignment with the spatial reference systems used in the prototype. Tools such as py3Dtilers were tested to convert IFC files into 3D tiles for CesiumJS, but further difficulties arose during coordinate transformations—from the Estonian system (EPSG:3301) to Cesium’s ECEF system (EPSG:4978)—highlighting the complexity of achieving spatial coherence across platforms.

To address these issues, a Python script was developed to parse IFC files into geometric and thematic data, which were then stored in separate database tables. Linking the geometry (e.g., tiles, tiles_metadata) with attributes (e.g., kaja_ifc, kaja_ifc_properties, and kaja_ifc_materials) required careful schema design and handling of complex relationships. This integration was essential to enable seamless querying and visualisation of LADM-based legal and administrative information within the 3D environment, ensuring that both spatial accuracy and semantic richness were preserved in the prototype.

Finally, in response to **Sub-RQ7c "How can the applicability of the reference cadastral survey workflow be validated?"**, the *LADM-based cadastral survey workflow has been validated through its application across three distinct international contexts*: Denmark, Greece, and Colombia (section 8.2). The reference workflow for cadastral surveying includes both administrative and surveying aspects, aligning with the conceptual refined survey model of ISO19152–2:2025. Together with the conceptual survey model, they are applicable to a range of spatial units, from land parcels to underground infrastructure and buildings. They lay the groundwork for further specialisation to meet the specific needs of countries and jurisdictions.

These three distinct cases demonstrate the adaptability and effectiveness of the proposed reference cadastral survey workflow in accommodating varying legal, organisational, and technical conditions. Denmark and Greece provide examples of parcel subdivision workflows within established and evolving LAS environments, respectively, while the Colombian case highlights the workflow's suitability for initial land rights registration, particularly in contexts involving community-based data collection.

In Denmark, a mature LAS is already in place, and the LADM survey model integrates seamlessly into existing cadastral processes. The model aligns with Denmark's established workflows, streamlining cadastral operations and ensuring compliance with national regulations. This demonstrates the workflow's capacity to optimise LA processes in advanced systems where data precision and legal compliance are paramount.

Greece's LAS is still under development. The workflow's flexibility allows it to cater to the evolving legal and technical requirements of the Hellenic Cadastre, while ensuring that cadastral records are updated and maintained consistently. The workflow also accommodates ongoing developments, making it suitable for countries which LASs are in transition. By providing a structured approach to cadastral surveying, the LADM model supports Greece's objectives of improving data integration, accuracy, and validation during the LAS development process.

The third case study, from Colombia, demonstrates the application of the LADM-based reference cadastral workflow in a post-conflict context. In this context, participatory data collection has been tested and integrated with professional surveying methods, allowing for the inclusion of informal and unregistered land rights. The flexibility of the LADM model to handle diverse data sources, from community-led efforts to formal cadastral records, has enabled Colombia to test the establishment of reliable land records in areas where traditional cadastral systems were insufficient, as LADM has been implemented in practice in the country. This case highlights the model's ability to facilitate rapid LA development in regions with complex land tenure situations and emphasises the importance of community engagement in land rights documentation.

Overall, it can be concluded that, the validation of the LADM-based cadastral survey workflow through these three case studies underscores its potential for global applicability. The workflow can support bridging gaps in system maturity, accommodating multiple generic workflows (parcel subdivision, initial registration), and supporting varying levels of stakeholder engagement. This universality underscores its potential to act as a standardised framework for cadastral workflows worldwide, enabling consistency while respecting local legal, cultural, and institutional contexts.

9 Conclusions and Future Research

In line with the Design Science Research methodology, this PhD research developed a new artefact, which is an information model for cadastral surveying, that incorporates both 2D and 3D professional and crowdsourcing survey techniques and aligns with international standards.

This final chapter presents the key outcomes and findings of the research, reflects on the research scope and offers directions for future research. The main research question and sub-questions are addressed, with the primary conclusion detailed in section 9.1. Additionally, a short reflection on the research journey (in section 9.2), as well as recommendations for further study and development are provided in section 9.3.

9.1 Key findings

The dissertation emphasises the importance of adopting international standards, particularly ISO 19152: LADM, to enable consistent, comparable, and scalable data collection for LA. It explores the evolving landscape of 3D LA, with a specific focus on standardisation efforts, technological advancements, and contribution to the revision of ISO 19152: LADM Edition II within the context of the Spatial Development Lifecycle.

The results of this research are set to contribute directly to various parts of ISO 19152 developed in LADM Edition II, with some of them already been adopted as ISO standards. Specifically, **the 3D spatial profiles developed as part of this dissertation are incorporated into Annex C of ISO 19152-2:2025**, enhancing the standard's capacity to manage multi-dimensional land units. **The LADM survey model, that has been adopted as a core component of ISO 19152-2:2025**, will further support land administration practices, bridging the gap between professional and participatory data acquisition methods. Additionally, **the reference cadastral survey workflow is planned to be included in ISO 19152-6 (specifically in Part 6a)**, ensuring that it serves as a guideline for LADM implementation processes and broader interoperability.

The research is driven by the primary question:

- **Main RQ - How to design, develop and evaluate efficient 3D Land Administration in support of the Spatial Development Lifecycle?**

Developing an efficient 3D LAS to support the SDL activities requires an **integrated legal, technical, and organisational approach.** This dissertation primarily addresses the technical aspects, with legal and institutional considerations regarded as preconditions rather than as the core focus. The research begins with a systematic literature review to meet fundamental principles and good practices, assessing the state-of-the-art in 2D and 3D LA through global reports, country-level implementations, and standardisation advancements. A key outcome of this analysis is identifying challenges and opportunities in standardising and implementing 3D LA systems.

From a **technical** standpoint, *this research identifies dominant standards supporting seamless data reuse across SDL applications, particularly in the surveying and design phases of 3D LA.* Ensuring compatibility with Spatial Data Infrastructures (SDIs) is crucial to integrate geospatial and LA-related datasets with broader urban planning and infrastructure applications. *The cadastral requirements' analysis set the basis for the development of LADM Edition II, Part 2 – Land Registration, focusing on surveying aspects.* The categorisation of 3D spatial units based on geometric complexity, ensuring a structured and standardised representation within LASs is part of the research's outcomes, as well as, the collection and analysis of LADM-based country profiles (Editions I and II) provide insights into standard adoption, highlighting areas for improvement and good practices.

The afore mentioned, provided input that was adopted by ISO19152-2:2025, ensuring that cadastral surveys can support 3D spatial data acquisition in a standardised manner, ensuring consistency, scalability, and practical applicability in diverse LASs. Various surveying methods and design-phase data sources are integrated to enhance accuracy and efficiency. A reference cadastral survey workflow is designed, offering a generic, standardised approach to 3D LA. Additionally, a methodological framework for developing LADM-based country profiles is presented, based on good practices and international experience.

The final part of this research focuses on the evaluation and iterative refinement of the developed artefacts, as presented in chapter 8. Validation was carried out at multiple levels: the conceptual survey model was tested using instance-level diagrams based on real-world case studies in Germany and Estonia, while the reference cadastral survey workflow was implemented and assessed in Denmark, Greece, and Colombia—highlighting its flexibility and scalability across varying contexts. Furthermore, a 3D web-based prototype was developed to demonstrate the integration of BIM and survey data within an interactive LA environment.

The research was strengthened through a standardisation feedback loop, with contributions shared and reviewed within ISO TC211 and OGC meetings. Additionally, further validation and implementation occurred also in the context of the H2020 GISCAD-OV project (under which this dissertation was funded) and the experts of the project's consortium. Dissemination efforts through academic channels, including conferences, workshops, and journal publications, further reinforced the relevance, scientific rigour, and applicability of the developed solutions.

As a graphic summary of SDL applications, Figure 9.1 illustrates the role of LADM Edition II in supporting the SDL and highlights the importance of standardisation in integrating LA processes across disciplines and jurisdictions. It specifically demonstrates how different LADM parts align with key SDL phases, ensuring interoperability, data consistency, sharing and reuse. Specifically:

1. **ISO 19152-2 (Land Registration)** is predominantly involved in surveying and registering, ensuring the recording of RRRs and their spatial representation. It plays a crucial role in linking cadastral and land registry data.
2. **ISO 19152-4 (Valuation Information)** contributes to financing, and evaluating, addressing aspects related to property valuation and taxation, as well as operating/ maintaining and renovating.
3. **ISO 19152-5 (Spatial Plan Information)** is primarily associated with planning/ zoning and provision of permits, ensuring land-use regulations, zoning requirements, and spatial planning considerations are properly integrated into development processes.

The distribution of LADM parts across the SDL phases reflects the multi-disciplinary nature of LA, showcasing the need for interoperability between geospatial, legal, and other aspects (financial, planning, etc.). LADM parts 2, 4 and 5 contribute to multiple SDL phases, supporting continuity and consistency in land-related decision-making.

Notably, the absence of ISO 19152-3 (Marine Georegulation) in this representation (Figure 9.1) implies that this part is more domain-specific, focusing on marine spatial units rather than general land-based development. Similarly, ISO 19152-6 (Implementation) is expected to be applicable across all SDL phases that align with the conceptual components of LADM. However, its exclusion from this figure is since the development of part 6 has not yet been initiated. Once developed, Part 6 will provide implementation guidelines, further strengthening LADM's practical application throughout the SDL.

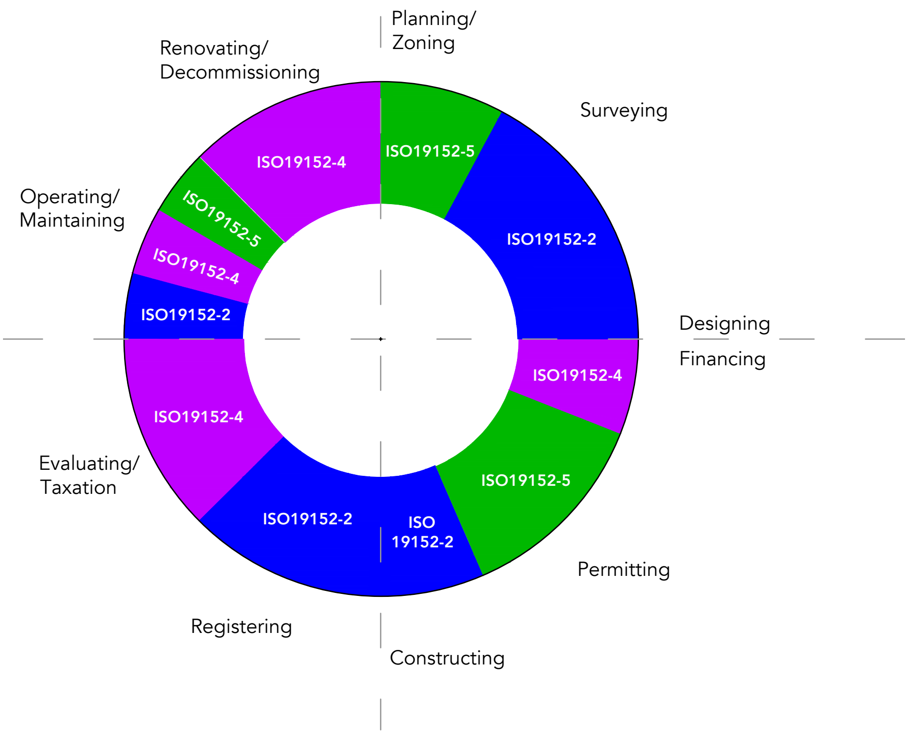

FIG. 9.1 LADM Edition II Parts supporting the various stages of the Spatial Development Lifecycle

Figure 102 visualises the SDL–LADM linkage, while the dissertation's contributions are the concrete models, workflows, and methodologies that operationalise this linkage and have already been adopted in ISO 19152-2:2025. Specifically, the contributions of the dissertation, as depicted in Figure 102 are:

- **Standardised 3D spatial profiles (ISO 19152-2:2025)** – The thesis developed profiles that extend LADM to properly capture 3D spatial units across SDL phases, particularly planning, construction, registration, and operation.
- **Cadastral survey model (ISO 19152-2:2025)** – It proposed a standardised cadastral survey information model to handle both professional and crowdsourced data, ensuring accuracy and consistency across the surveying, design, and registration phases.
- **Web-based 3D LA prototype** – As a proof of feasibility, the prototype demonstrated practical integration of survey and design data for SDL use cases (designing, registering, operating).
- **Data lifecycle concept** – The dissertation introduced reuse of data across SDL phases, strengthening interoperability between LADM parts (esp. Parts 2, 4, 5) and showing how valuation, spatial planning, and registration can interconnect.

The following sub-questions are posed to investigate different aspects of the main research question and below their responses are analysed.

- **Sub-RQ1 – What is the current state-of-the-art in 2D and 3D Land Administration worldwide as: a) documented by global reports and reported by countries and b) progressed by standardisation organisations**

To address this sub-question, the research examined two key dimensions:
(a) the practical implementation of 3D LASs across jurisdictions and
(b) advancements in standardisation, particularly through LADM Edition II.

The first conclusion and answer to the **Sub-RQ1a** refers to the findings from the **analysis of the 4th FIG Questionnaire on 3D LA**, that was conducted in the context of this dissertation and refers to the period 2022–2026, as presented in chapters 2 and 7. Specifically:

1. Many countries are in transition, experimenting with pilot projects or integrating 3D attributes into existing 2D cadastral systems. The research findings provide an assessment of the current landscape reflecting a gradual but uneven transition towards more advanced 3D LASs,
2. Legislative, technological, and organisational challenges remain major barriers to full adoption of 3D LA,
3. The most common types of 3D spatial units recorded include condominiums and apartments, but these are often not explicitly registered as 3D,

4. Some countries do not distinguish between 2D and 3D spatial units' registration, making global comparisons difficult,
5. Statistical inconsistencies persist due to different data collection methods, particularly in defining 3D parcels and determining whether their geometry is formally surveyed or simply indexed in 3D, and:
6. Adoption of LADM is increasing, with 35% of surveyed countries aligning their cadastral databases with LADM, though compliance levels vary.

With regards to the **ranking of countries in 3D LAS implementation** it is observed that *the research underscored variations in the perception, registration, and implementation of 3D LASs, underpinning the need for harmonised methodologies and standardised data models.* An initial rubric-based evaluation is developed to systematically assess the progress of countries implementing 3D LAS.
The rankings revealed:

1. Technologically pioneering countries (e.g., The Netherlands, South Korea, Queensland, Finland, Malaysia, Shenzhen, Singapore) show progress in digital cadastres and 3D spatial units, and:
2. Other jurisdictions face challenges in transitioning from paper-based systems, adapting 3D data models, and aligning legal frameworks.

With regards to **international organisations' role in LA reforms**, from the research carried out in the context of this dissertation, it is concluded that:

1. In addition to national efforts, international organisations such as the World Bank, UN-Habitat, and FIG are actively supporting LA reforms to formalise property rights and enhance LA services,
2. LASs contribute to monitoring progress towards international development goals, such as the SDGs.

Addressing **Sub-RQ1b**, as presented in chapter 4, conclusions on the state-of-the-art in 2D and 3D LA as progressed by standardisation organisations can be summarised as follows:

1. The continuous development of the LADM has played a pivotal role in shaping the standardisation of 2D and 3D LA worldwide. It has enabled countries to develop national profiles aligned with their specific legal and institutional frameworks while ensuring interoperability at a global level. The inventory of LADM-based country profiles presented in this dissertation, showcases how nations have customised LADM to align their legal, institutional, and cadastral frameworks, demonstrating LADM's adaptability to diverse LASs,

2 LADM has been aligned with several global initiatives aiming at improving land tenure security and governance, including the UN SDGs, FFPLA, and the GLII, reinforcing LADM's role as a reference model for sustainable land governance,
3 Beyond ISO, CEN and INSPIRE have contributed to the harmonisation of geospatial data at the European level, with High-Value Datasets (HVDs) under the Open Data Directive incorporating cadastral parcels as a key dataset. Furthermore, LADM's integration with initiatives such as the UN SDGs, FFPLA, and the GLII, as listed in the literature, has further reinforced its role in improving land tenure security and ensuring sustainable land governance. To further strengthen the implementation of LADM, the OGC established an LADM SWG in June 2024 to support the practical adoption of LADM across different software solutions. This initiative aligns with broader global trends in data governance and interoperability, ensuring that LADM remains a dynamic and adaptable standard for LA,
4 LADM Edition II represents a significant evolution of the original standard. While Edition I primarily focused on tenure, the second Edition has expanded to include land value, land use, and land development. The continued refinement and operationalisation of LADM through its second Edition and integration with emerging technologies and data infrastructures are expected to further advance 2D and 3D LA standardisation. The incorporation of new functions, such as valuation and spatial planning, ensures that LADM remains relevant and aligned with evolving LA practices.

These conclusions highlight the critical role of standardisation organisations in shaping the global landscape of land administration, reinforcing LADM as a key enabler for harmonised and efficient land governance from data management perspective.

- **Sub-RQ2 – Which standards can support data reuse in the context of SDL, particularly in the context of 3D Land Administration?**

The reuse of data in the SDL, particularly in 3D LA, relies on vendor-neutral, standardised data models to facilitate interoperability, integration, and accessibility across geospatial, LA and AECOO domains. A major challenge, identified through this research, is the seamless integration of AECOO data with land-related and geospatial data while maintaining high-quality and reusable information across different SDL phases.

Concluding chapter 3 and answering **Sub-RQ2**, it is identified that several standards support data reuse and interoperability in 3D LA, with the most dominant being:

1 LADM (ISO 19152),
2 IFC (ISO 16739-1),

3. OGC LandInfra, and:
4. CSDM (Cadastral Survey Data Model).

These four standards were selected for examination in this dissertation due to their direct relevance to 3D LA and/ or their established or emerging role in supporting data reuse within the SDL. It is noted that while LADM, IFC, and LandInfra are widely recognised international standards, CSDM, though a national initiative, is highly relevant due to its structured approach to cadastral survey data management, making it applicable in 3D LA.

Other standards, such as INTERLIS, are acknowledged for their potential role in data exchange and interoperability. However, they were not examined in detail as they do not provide the same level of direct integration with the LA and cadastral processes required for this research, or they do not align with the latest technological trends in the field. The selection of these four standards ensures that the research focuses on frameworks that are both conceptually robust and practically applicable to 3D LA challenges.

- **Sub-RQ3 – a) What are the main types of 3D spatial units based on the complexity of their geometry and b) how can they be described in a standardised way?**

A categorisation of 3D spatial units according to their geometric and legal complexity, providing a structured approach to their management within LASs is presented in chapter 5. By classifying spatial units based on their characteristics, this research supports data integration, visualisation, and interoperability across different jurisdictions and legal frameworks.

3D spatial units vary in complexity depending on factors such as data availability, regulatory requirements, and market demands. These units can be classified into: basic 3D units, which are represented as single points, simple surfaces, or extruded 2D parcels; intermediate 3D units, which include volumetric parcels with clear legal boundaries, such as condominiums or underground spaces; and complex 3D units, which encompass multi-layered ownership structures, subterranean networks, air rights, and legally defined 3D spaces that require high-precision modelling. To support data interoperability and reuse, this dissertation explores two primary sources of 3D spatial unit data: surveying data and design data. Technologies such as UAVs, GNSS, and LiDAR facilitate acquisition of accurate spatial data, contributing to better 3D modelling, land registration, and transparent urban governance.

In response to **Sub-RQ3b**, chapter 6 concludes to a standardised way of describing 3D spatial units by developing the 3D spatial profiles (which are included in Annex C of ISO 19152-2:2025a). These profiles, responding to the increasing demand for detailed 3D representation and registration, support mixed 2D/3D representations and accommodate country-specific needs, while aligned with the 'Continuum of Spatial Units' requirement of LADM Edition II (Requirement 2-12), supporting interoperability across disciplines and lifecycle phases in 3D LA. The spatial profiles are:

- Simple 3D Spatial profile
- 3D General Boundary Spatial profile
- 3D General Spatial Unit profile
- 3D Spatial profile for single-valued stepped spatial units
- 3D Spatial profile for multi-valued stepped spatial units
- 3D Spatial profile for balanced spatial units

- **Sub-RQ4 – a) Which are the cadastral surveying requirements? b) Based on these, how can the survey model for LADM Part 2- Land Registration be developed?**

Chapter 4 outlines the key cadastral surveying requirements **(Sub-RQ4a)**, also included in LADM Edition II (Part 2 – Land Registration). Feedback from international standardisation bodies on defining these requirements, ensures alignment with global LA needs, addressing technical, legal, and organisational complexities.

These requirements ensure that LA data is managed in a distributed, standardised, and transparent manner, enabling multi-organisation collaboration, dynamic updating, and tracing history. LADM Edition II strengthens cadastral surveying through a structured, interoperable framework that supports seamless data integration, accuracy and adaptability, enabling scalable and efficient LASs.

Summarising, the requirements include:

1. Authentic source documents and traceable updates (Req. 2-6, 2-7) to ensure transparency in cadastral transactions and strengthen legal certainty in dispute resolution and land transactions,
2. Accountability (Req. 2-8) by supporting that cadastral transactions are being linked to responsible authorities, reinforcing governance and legal compliance.
3. Comprehensive representation of spatial units (Req. 2-12) covering text-based descriptions, point coordinates, and 3D volumetric representations for enhanced cadastral mapping.
4. Unique identifiers for spatial units (Req. 2-13) to ensure seamless integration, consistency, and efficient management of LA records.

5 Accurate georeferencing and support for multiple surveying methods (Req. 2-15, 2-16) to differentiate between legal and physical boundaries with coordinates collected using GNSS, UAVs, photogrammetry, and conventional surveys.
6 High-quality and reliable cadastral data (Req. 2-17) to ensure completeness, accessibility, and topological consistency, facilitating automated validation and improved LA- data management.

Chapter 6 presents the LADM cadastral survey model **(Sub-RQ4b)**, which integrates both professional and participatory land-rights recordation processes to improve inclusivity, precision, and adaptability in cadastral data collection. By aligning with OGC LandInfra and ISO 16739-1:2024 (IFC), the model ensures interoperability, flexibility, and scalability across cadastral workflows. The inclusion of LA_ DesignSource enhances efficiency by using design-phase data, reducing redundancy, and streamlining land registration processes.
One of the innovations of this model is the integration of Galileo High Accuracy Services (HAS), improving spatial data precision through satellite-based corrections for reliable boundary delineations and high-accuracy cadastral mapping. LA_SurveySource supports inclusion of observations from various surveying methods (GNSS, UAVs, photogrammetry, and conventional surveys), while LA_GNSSCorrection records coordinate uncertainties, ensuring compatibility with multiple GNSS systems. The incorporation of Observational State Representation (OSR) and State Space Representation (SSR) strengthens structured correction frameworks.

The scalable and adaptable LADM cadastral survey model accommodates evolving cadastral needs, future GNSS advancements, and high-accuracy positioning requirements. Its modular structure supports flexible data acquisition and reuse, making it applicable across diverse legal, institutional, and technological contexts. This structured yet adaptable model, included in ISO19152-2, positions the LADM survey model as a robust solution for modern LASs.

— **Sub-RQ5 –How can a generic, reference LA workflow be designed, built upon the survey model for LADM Part 2- Land Registration??**

Chapter 6 presents a reference cadastral survey workflow that integrates administrative and technical aspects, ensuring adaptability to diverse national contexts. By aligning with the refined survey model of ISO 19152-2, the workflow -developed in the context of this dissertation- facilitates seamless stakeholder collaboration, including land professionals, regulatory agencies, and citizens, enhancing the reliability of land-rights documentation. Designed to be both standardised and flexible, it provides a structured approach that accommodates variations in legal and institutional frameworks while ensuring consistency in land registration practices.

The workflow complies with key LADM Part 2 survey requirements, as outlined in sub-section 4.2.1, ensuring standardisation, transparency and efficiency in cadastral surveying. It maintains spatial data within SDI (Requirement 2-5), guaranteeing that authoritative records remain consistent and up to date. It enforces unique identifiers for spatial units and records (Requirement 2-13), supporting seamless data management and interoperability. The workflow further integrates spatial the use and processing sources from surveys and design documents (Requirement 2-14), accommodates multiple surveying methods (Requirement 2-15), and supports coordinate transformations (Requirement 2-16), ensuring compatibility with various geodetic reference systems. Data quality and consistency (Requirement 2-17) are safeguarded through rigorous quality control steps embedded within the workflow, reinforcing data reliability, accessibility, and usability.

Furthermore, the workflow contributes directly to the advancement of 3D LA standardisation, as it is planned for inclusion in ISO 19152-6, providing a structured guideline for LADM implementation and promoting broader interoperability. By formalising cadastral workflows through this model, LA systems can achieve greater efficiency, inclusivity, and accuracy, supporting the development of accessible 3D LA solutions globally.

— Sub-RQ6 – What steps should a country follow to develop a LADM-based country profile?

The development of an LADM-based country profile requires a structured approach tailored to the specific legal, institutional, and technical context of a country. Chapter 7 analyses the varying strategies adopted worldwide, with digitally advanced countries refining their profiles for enhanced interoperability and others, such as Nepal and Kenya, focussing on foundational legal and institutional capacity building. A key insight is the necessity for a collaborative approach, engaging academia, government institutions, and private sector stakeholders to ensure both theoretical robustness and practical applicability. Additionally, beyond profile creation, successful adoption depends on profile validation, stakeholder training, and effective dissemination strategies.

To formalise the process effectively, a three-phase iterative methodology is developed in the context of this dissertation. The first step “Scope Definition” involves identifying national priorities, assessing existing LAS frameworks, and engaging key stakeholders to define the objectives of the profile. The second one "Profile Creation" focuses on developing conceptual (UML) models based on LADM core classes while allowing for country-specific adaptations and code lists population, ensuring alignment with both national regulations and international standards. As a last step, "Testing and Implementation" translates conceptual models into database schemas, validates them with real-world datasets, and incorporates technological advancements such as 3D visualisation and enhanced querying capabilities.

This iterative methodology ensures continuous refinement, balancing global standardisation with national adaptability. The transition toward 3D LAS depends on legal, organisational, and technical readiness, requiring investment in education, stakeholder engagement, and financial resources. The proposed methodology provides a clear roadmap for aligning national LA systems with international standards while addressing country-specific needs, ensuring structured and scalable LADM adoption.

- **Sub-RQ7- How can the applicability and functionality of the survey model for LADM Part 2- Land Registration be validated a) at conceptual level; b) at a 3D web-based platform and**
  c) how the applicability of the reference cadastral survey workflow can be validated?

The validation of the new artefact developed in this PhD dissertation is achieved with regards to three key aspects, as presented in chapter 8:

I Conceptual-level validation (Sub-RQ7a)

The refined cadastral survey model for LADM Part 2 was validated at the conceptual level using instance-level diagrams derived from real-world case studies in Germany and Estonia. These cases, conducted within the H2020 GISCAD-OV project, demonstrated the model's ability to accommodate diverse cadastral workflows while integrating modern surveying technologies such as Galileo HAS corrections. The validation confirms that all necessary classes and attributes are accurately modelled, ensuring alignment between survey accuracy requirements and legal constraints. Furthermore, the conceptual model underwent extensive expert review in ISO TC211 and OGC meetings, where feedback from standardisation bodies and industry stakeholders refined its interoperability, compliance, and scalability. This iterative process reinforced both the theoretical robustness and practical applicability of the model.

II Validation via 3D web-based prototype (Sub-RQ7b)

A 3D web-based prototype has been developed to assess the survey model's applicability in digital environments, enabling interactive visualisation, querying, and validation of cadastral data. Built using CesiumJS, PostgreSQL/PostGIS, and a Node.js backend, the prototype integrates BIM and 3D GIS data within an LADM-compliant framework. The prototype enables users to query spatial units, retrieve legal and administrative records, and visualise 3D legal spaces within an interactive interface. It has been tested using the IFC model of the Kaja Cultural Centre in Tallinn, Estonia, alongside real cadastral survey data. GNSS observations stored within the LADM survey model are also integrated, demonstrating seamless linkage between cadastral registration and design sources. This prototype successfully showcases the feasibility of integrating survey and design data into a dynamic, standardised 3D LA system (http://159.223.219.149/). ++ GitHub link

One of the main challenges encountered during the development of the 3D web prototype was the handling of georeferencing inconsistencies present in the IFC models. These issues were closely tied to the version of the IFC file provided— while IFC4 offers improved support for georeferencing, older versions, such as IFC2x3, which lacks robust spatial referencing capabilities. As a result, aligning the BIM-derived geometry with the spatial reference system used in the rest of the prototype required additional preprocessing and manual adjustments to ensure consistency and accurate spatial positioning.

In this context, the py3Dtilers tool[33] was explored to convert IFC files into 3D tiles suitable for visualisation in CesiumJS. However, various difficulties emerged during the conversion process, particularly with the transformation of coordinates from the Estonian national system (EPSG:3301) into global reference systems. Cesium operates using the Earth-Centred, Earth-Fixed (ECEF) coordinate system (EPSG:4978), adding an extra layer of complexity in maintaining spatial coherence.

To ingest IFC data into the backend database, a Python-based parser was developed, which extracted both geometric and non-geometric information. This resulted in two main groups of tables: one set for geometric data (used in 3D tile generation and rendering) and another for thematic data derived from the IFC structure. Integrating these datasets within a single relational database posed another significant technical hurdle. It required establishing robust associations between the 3D tile geometry tables (tiles and tiles_metadata) and the IFC-derived thematic tables (kaja_ifc, kaja_ifc_properties, and kaja_ifc_materials).

33 https://github.com/VCityTeam/py3Dtilers

This integration was essential for enabling interactive querying and visualisation of legal and administrative information linked to spatial units in the 3D environment. Achieving this functionality involved designing appropriate relational mappings and managing many-to-many relationships, particularly in complex models where components are shared across multiple elements. These efforts were fundamental to ensuring that the prototype not only displayed 3D geometries accurately but also allowed meaningful interaction with the underlying LADM-compliant LA data.

III Validation of the reference cadastral survey workflow (Sub-RQ7c)

The LADM-based reference cadastral workflow has been validated through case studies in Denmark, Greece, and Colombia, showcasing its adaptability across different legal, technical, and institutional contexts. In Denmark, where a mature LAS exists, the workflow seamlessly integrated with existing cadastral processes, optimising data consistency and interoperability. In Greece, where the LAS is still under development and transition, the workflow facilitates the transition to digital LASs, demonstrating flexibility in evolving LA environments. In Colombia, the model successfully supported participatory LA testing at the initial registration phase, by integrating informal land rights documentation with professional cadastral surveys, proving effective in post-conflict areas.

These case studies confirm that the reference workflow is applicable to LASs at different maturity levels, reinforcing its role in standardising and harmonising cadastral practices globally. The adaptable nature of the workflow ensures that it can be tailored to diverse cadastral requirements, paving the way for the future development of 3D LASs.

9.2 Reflection

3D LASs are increasingly recognised as crucial tools for addressing the spatial and legal complexities of modern, urban environments, responding to rising public expectations for accurate and interactive 3D information—expectations that, in many cases, already exceed current legal requirements. This dissertation contributes to this evolution of 3D LASs by exploring how information from earlier phases of the Spatial Development Lifecycle (SDL) can be reused, leveraging international standards and emerging technologies.

This research journey has been both intellectually stimulating and practically challenging, as it required navigating in the domains of LA, geospatial data management, and legal and institutional complexities. It does not only contribute to academic knowledge, but also influences ongoing global standardisation efforts and shaped best practices for modernising/ updating LASs. The research methodology adopted ensures that findings are both theoretically sound and practically applicable. The research is driven by the limitations of traditional 2D LAS, in line with the opportunity to leverage technological advancements to efficiently address their complexities.

A crucial aspect of this research is the interdisciplinary collaboration, particularly engagement with ISO TC211 and OGC, bridging academic research with real-world applications. Through iterative discussions in these standardisation bodies, the research contributes directly to ISO 19152-2:2025 (as parts of the dissertation are adopted in the ISO) and provides insights into integrating Galileo High Accuracy Service (HAS) for cadastral surveying as part of the EU Horizon 2020 GISCAD-OV project. These collaborations ensure scalability, adaptability, and practical feasibility.

Integrating design phase information into LA requires standardised data formats, legal recognition, and technological compatibility. Using BIM/IFC models, based on detailed guidelines and requirements, and LADM, enhances interoperability across SDL processes, ensuring seamless data transfer and improving data consistency. Legal and regulatory adjustments are essential to formally recognise digital documents and models in LA. A key principle is that data should be collected once and then shared and reused multiple times, via SDI/ Geographical Information Infrastructure (GII). It should be stored at its authoritative source, and maintained by responsible organisations, ensuring alignment with open and private or restricted data standards.

A challenge in this research is the complexity of standardising cadastral survey models and workflows across jurisdictions with distinct legal frameworks. The proposed LADM survey model, as well as the reference cadastral workflow integrate professional and community-based data acquisition, promoting inclusivity and broad representation of land rights. A shift toward democratising LAS. Moreover, the LADM-based country profile methodology provides a structured approach to harmonising LA terminology and modelling allowing local adaptations. Aligning national LAS with international good practices enhances comparability, consistency, and interoperability.

This dissertation makes the following **key contributions** to 3D LA, standardisation, and cadastral surveying:

1. **Developing parts of LADM Edition II** by providing a standardised information model for cadastral surveying,
2. **Empirical evaluation of 3D LA** by analysing the "4th FIG Questionnaire on 3D Land Administration", and:
3. **Standardisation and practical implementation** by developing a web-based 3D LA prototype integrating survey and design sources, demonstrating how standards-based implementations can improve interoperability, data quality, and reusability.

Beyond the academic and professional impact, this research journey has been personally transformative.

9.3 Recommendations for future research and developments

This dissertation serves as a foundation for future advancements in 3D LA, standardisation, and cadastral surveying. The work conducted here lays the groundwork for continued research and collaboration, ensuring that LAS remain adaptable, transparent, and responsive to the evolving needs of societies worldwide. The research contributes directly to ISO 19152-2:2025 (Land Registration) and ISO 19152-6 (Implementation), offering a foundation for further refinement, validation, and operationalisation of the LADM Parts in diverse contexts.

The evolution of 3D LA is not solely a technical challenge but also involves legal, organisational, and institutional transitions. While technical solutions and standards are maturing, their adoption in practice requires multi-stakeholder engagement, legal and institutional adjustments, and further validation through pilot implementations. Challenges related to data governance, interoperability, and awareness among data producers, citizens, users and policymakers regarding the benefits of data sharing and standardised approaches shall be further addressed.

The following key areas highlight the future research directions of this dissertation:

I Advancing LADM standardisation and implementation

1 Further refinement of LADM Edition II requires ensuring compatibility across different parts of the standard, refining conceptual semantics, and formalising encoding agreements. Expanding 3D capabilities across all LADM parts is essential for achieving a comprehensive LA, while real-world testing of spatial profiles is necessary to refine conceptual models and improve interoperability. Additionally, the development of LADM-compliant database schemas and validation services will support structured deployment, ensuring automated compliance checks based on Annex A of ISO 19152-1:2024. Systematic evaluations of 3D LA implementations using structured assessments and metadata-driven reporting will provide valuable insights into legal, organisational, and technical improvements at both national and regional levels.

2 The LADM survey model and the reference cadastral survey workflow require further validation particularly regarding the integration of HAS-based GNSS corrections and participatory data collection across various jurisdictions. In this context, establishing

TOC

encoding agreements with survey equipment manufacturers and software providers is crucial to ensure LADM compliance and seamless integration into industry products. Strategies shall also be developed to support manufacturers in maintaining long-term compatibility with LADM, ensuring the sustainability of standardised cadastral and LA solutions. Furthermore, the reference cadastral survey workflow should be tested through real-world pilot projects to refine roles, responsibilities, and identify implementation gaps. In this scene, it shall also be tested in less formal land markets or jurisdictions without existing LA infrastructure to strengthen its global applicability.

3 To improve LAS performance measurement and the integration of LA indicators, the development of reliable evaluation mechanisms is crucial for assessing LAS performance across different jurisdictions. Further formalisation of 3D LA indicators will support the monitoring of SDG-related land governance goals through LADM Part Additionally, exploring synergies between LADM and other ISO standards will enhance the accuracy and effectiveness of these indicators, ensuring a more structured approach to performance tracking and system improvements.

4 Future research should explore a cost-benefit analysis of LADM adoption, focusing on its scalability and sustainability in 3D LA implementations. This analysis will provide insights into the economic feasibility, efficiency gains, and long-term benefits of LADM-based LASs. In parallel, a roadmap per primary stakeholder of LA (e.g. national mapping agencies, surveyors, notaries, urban planners, etc.) shall be developed in line with the developed tools of this dissertation to enhance its utility in policy and operational environments.

II BIM-Legal for3D LA

Developing a BIM-Legal reference workflow to facilitate the registration of RRRs and their corresponding spatial units within an LADM-based database. Reusing BIM files submitted for building permits for RRR registration and implementing rule-based permitting checks will improve efficiency and integration. Refining BIM-Legal model validation by ensuring compliance with BIM standards and legal source documents is essential for reliability in LA and property registration. Active engagement of notaries and land registries will support the validation of 3D legal spaces and 2D division drawings derived from BIM models. Additionally, enhancing data interoperability by aligning BIM representations with contractual descriptions of rights will strengthen the connection between spatial and legal information in LA systems.

III Strengthening Interoperability Across SDL

Future research should focus on expanding standardisation beyond land parcels to include buildings and infrastructure, ensuring legal and geospatial compatibility with standards such as OGC LandInfra and CityGML. Enhancing cooperation between ISO TC211, OGC, buildingSMART International, and IHO will promote cross-domain interoperability. The OGC LADM SWG should be leveraged to refine LADM encodings, while addressing proprietary software silos through open APIs, standardised data formats, and support for complex geometries.

IV Strengthening Technological Capabilities for 3D LA

Advancements in AI, machine learning, and linked data will enhance data accessibility, scalability, and efficiency in 3D LA workflows. AI-driven validation tools will improve data quality in LADM-based databases, while blockchain and smart contracts can automate land transactions and integrate with planning and valuation datasets. Smart Cities and Digital Twins initiatives should explore real-time property transactions, automated compliance checks, and digital triplets for dynamic land registration updates.

The web-based 3D LA prototype could be further developed to expand the database with more infrastructure elements, integrate Augmented Reality (AR) tools for real-time visualisation of spatial units and RRRs, and use AI-driven image recognition for automated parcel delineation. Implementing edge computing could improve data processing efficiency, while harmonising heterogeneous datasets could enhance interoperability. Additional improvements shall include support for Level of Detail (LoD) visualisation and enable 3D editing of spatial and legal records.

V Enhancing legal, institutional, and governance frameworks

Beyond technical advancements, successful 3D LA adoption requires legal and regulatory reforms, including data governance policies, access rights, and IP protection for BIM models. Sustainable business models for data providers should balance private and public interests, while awareness campaigns should promote citizen engagement through crowdsourced survey data. Formal recognition of BIM models as a legitimate 3D LA source should be reinforced at national and EU levels, incorporating machine-readable legislative rules into LASs and defining blockchain-based transaction standards.

VI Deepening insights from FIG Questionnaires on 3D LA

Further analysis is needed to refine questionnaire-based assessments on 3D LA implementation. Enhancing the rubric-based framework will allow tracking progress in 3D LAS adoption and support more structured evaluations of global implementation trends.

By addressing these challenges, future research will help shape more resilient, interoperable, and sustainable 3D LASs.

Bibliography

Aditya, T., Laksono, D. P., Atunggal, D., Susanta, F. F., Widjajanti, N., Setiawan, M. B., Agam, N., & Wibisono, T. 3D modelling, validation and visualization of 3D parcels in first registration for 3D cadastre – Indonesia case. In Proceedings of the 7th International FIG 3D Cadastre Workshop. New York, USA.

Aditya, T., Sucaya, I. K. G. A., & Nugroho Adi, F. (2021). LADM-compliant field data collector for cadastral surveyors. *Land Use Policy*, 104, 105352. https://doi.org/10.1016/j.landusepol.2021.105352.

Aditya, T., Unger, E. M., van den Berg, C., Bennett, R., Saers, P., Lukman Syahid, H., Erwan, D., Wits, T., Widjajanti, N., Budi, Santosa, P., Atunggal, D., Hanafi, I., & Sutejo, D. (2020). Participatory land administration in Indonesia: Quality and usability assessment. *Land*, 9(3), 79. https://doi.org/10.3390/land9030079.

Aien, A., Rajabifard, A., Kalantari, M., & Williamson, I. (2011). Aspects of 3D cadastre – A case study in Victoria. *In Proceedings of FIG Working Week 2011: Bridging the Gap between Cultures, Marrakech, Morocco*, 18–22 May 2011.

Alattas, A. (2022). *The integration of LADM and IndoorGML to support the indoor navigation based on the user access rights*. PhD dissertation, Delft University of Technology.

Alattas, A., Kalogianni, E., Alzahrani, T., Zlatanova, S., & van Oosterom, P. (2021). Mapping private, common, and exclusive common spaces in buildings from BIM/IFC to LADM: A case study from Saudi Arabia. *Land Use Policy*, 104, 105355. https://doi.org/10.1016/j.landusepol.2021.105355.

Alattas, A., Zlatanova, S., van Oosterom, P. J. M., Chatzinikolaou, E., Lemmen, C. H. J., & Li, K.-J. (2017). Supporting indoor navigation using access rights to spaces based on combined use of IndoorGML and LADM models. *ISPRS International Journal of Geo-Information*, 6(12), 384. https://doi.org/10.3390/ijgi6120384.

Alattas, A., van Oosterom, P. J. M., & Zlatanova, S. (2018). Deriving the technical model for the indoor navigation prototype based on the integration of IndoorGML and LADM conceptual model. In 7th *International FIG Workshop on the Land Administration Domain Model* (pp. 245–267). Zagreb, Croatia.

Alattas, A., van Oosterom, P. J. M., Zlatanova, S., Hoeneveld, D., & Verbree, E. (2020). LADM-IndoorGML for exploring user movements in evacuation exercise. *Land Use Policy*, 98, 104154. https://doi.org/10.1016/j.landusepol.2020.104154.

Andrée, M., Paasch, J. M., Paulsson, J., & Seipel, S. (2018). *BIM and 3D property visualisation*. In Proceedings of the FIG Congress, Istanbul, Turkey.

Atazadeh, B. (2017). *Building information modelling for urban land administration*. PhD dissertation, The University of Melbourne.

Atazadeh, B., Halalkhor Mirkalaei, L., Olfat, H., Rajabifard, A., & Shojaei, D. (2021a). Integration of cadastral survey data into building information models. *Geo-Spatial Information Science*, 24(3), 387–402. https://doi.org/10.1080/10095020.2021.1937336.

Atazadeh, B., Kalantari, M., Rajabifard, A., & Ho, S. (2017b). Modelling building ownership boundaries within BIM environment: A case study in Victoria, Australia. *Computers, Environment and Urban Systems*, 61, 24–38.

Atazadeh, B., Kalantari, M., Rajabifard, A., Ho, S., & Ngo, T. (2017c). Building information modelling for high-rise land administration. *Transactions in GIS*, 21, 91–113. http://dx.doi.org/10.1111/tgis.12199.

Atazadeh, B., Olfat, H., Rajabifard, A., Kalantari, M., Shojaei, D., & Marjani, A. M. (2021b). Linking land administration domain model and BIM environment for 3D digital cadastre in multi-storey buildings. *Land Use Policy*, 104, 105367.

Atazadeh, B., Rajabifard, A., & Kalantari, M. (2017a). Assessing performance of three BIM-based views of buildings for communication and management of vertically stratified legal interests. *ISPRS International Journal of Geo-Information*, 6(7), 198. https://doi.org/10.3390/ijgi6070198.

Augustinus, C., Lemmen, C. H. J., & van Oosterom, P. J. M. (2006). Social tenure domain model – Requirements from the perspective of pro-poor land management. *In 5th FIG Regional Conference: Promoting Land Administration and Good Governance, March 8–11*, 2006, Accra, Ghana.

Borrmann, A., König, M., Koch, C., & Beetz, J. (2015). *Building Information Modelling: technologische Grundlagen und industrielle Praxis.* (VDI-Buch). Springer. https://doi.org/10.1007/978-3-658-05606-3.

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). Building Information Modelling: Why? What? How? In *A. Borrmann, M. König, C. Koch, & J. Beetz* (Eds.), Building Information Modeling. Springer.

Broekhuizen, M., Kalogianni, E., & van Oosterom, P. J. M. (2021). BIM models as input for 3D land administration systems for apartment registration. *In Proceedings of the 7th International FIG 3D Cadastre Workshop*, 53–74.

Broekhuizen, M., Kalogianni, E., & van Oosterom, P. J. M. (2025). BIM/IFC as input for registering apartment rights in a 3D land administration system – A prototype webservice. *Land Use Policy*, 148. https://doi.org/10.1016/j.landusepol.2024.107368.

BuildingSMART. (2019). *Open BIM standards*. https://www.buildingsmart.org/standards/.

Butler, H., Daly, M., Doyle, A., Gillies, S., Hagen, S., & Schaub, T. (2016). *GeoJSON (7946)*. https://datatracker.ietf.org/doc/html/rfc7946.

COWI. (2018). *Review SOLA Suite of Applications: Final report*. https://www.fao.org/fileadmin/templates/nr/sola/documents/Review_SOLA_Suite_of_Applications_-__Final_Report_20181221.pdf.

Cadastre and Land Registry Knowledge Exchange Network (CLRKEN). (2015). *Documentation of 'Public–Law Restrictions'*. Eurogeographics.

Cemellini, B., van Oosterom, P. J. M., Thompson, R., & De Vries, M. (2020). Design, development and usability testing of an LADM compliant 3D cadastral prototype system. *Land Use Policy*, 98. https://doi.org/10.1016/j.landusepol.2019.104418.

Cerba, O. (2010). *Conceptual data models for selected themes (D4*.2). Plan4all. ECP-2008-GEO318007. https://otik.uk.zcu.cz/bitstream/11025/6217/1/d4–2conceptualdatamodelsforselectedthemes-101201033602-phpapp01.pdf.

Chehrehbargh, F., Rajabifard, A., Behnam, A., & Steudler, D. (2024). Identifying global parameters for advancing land administration systems. *Land Use Policy*, 136(C).

Chen, M. (2024). *Formalizing land indicators for SDGs: Implementation and evaluation using international standards*. MSc thesis, Delft University of Technology.

Chen, M., van Oosterom, P. J. M., Kalogianni, E., & Dijkstra, P. (2023). SDG land administration indicators based on ISO 19152 LADM. *11th International FIG Land Administration Domain Model / 3D Land Administration Workshop*, 11–13 October 2023, Gävle, Sweden. http://www.gdmc.nl/3DCadastres/workshop2023/programme/3DLA2023_paper_F.pdf.

Chen, M., van Oosterom, P. J. M., Kalogianni, E., Dijkstra, P., & Lemmen, C. H. J. (2024). Bridging sustainable development goals and land administration: The role of the ISO 19152 land administration domain model in SDG indicator formalization. *Land*, 13(4), Article 491. https://doi.org/10.3390/land13040491.

Chipofya, M., Karamesouti, M., Schultz, C., & Schwering, A. (2020). Local domain models for land tenure documentation and their interpretation into the LADM. *Land Use Policy*, 99. https://doi.org/10.1016/j.landusepol.2020.105005.

Chudasama, C. (2024). *Top countries leading BIM adoption in 2024: Global insights*. https://caddraftingservices.in/blog/leading-countries-in-global-bim-adoption/.

Clemen, C., & Gründig, L. (2006). *The Industry Foundation Classes (IFC): Ready for indoor cadastre? In Proceedings of the Twenty-third International FIG Congress, Munich, Germany*.

Dimopoulou, E., Karki, S., Roić, M., de Almeida, J. P. D., Griffith-Charles, C., Thompson, R., Ying, S., Paasch, J., & van Oosterom, P. J. M. (2018). *3D cadastres best practices, Chapter 2: Initial registration of 3D parcels*. In Proceedings of the FIG Congress, Istanbul.

ESRI. (2024). *LADM in ArcGIS*. https://storymaps.arcgis.com/stories/b8c187c1864344ffab21e9eaf638a6b4.

EU BIM Task Group. (2021). *Accelerating the green, digital and resilient transition by implementing building information modelling in public procurement*. EU BIM Task Group Position Paper. https://eubim.eu/wp-content/uploads/2022/12/21-12-17-EUBTG-position-paper-FINAL.pdf.

Eastman, C. M. (2011). *BIM handbook: A guide to building information modelling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Einali, M., Alesheikh, A. A., & Atazadeh, B. (2022). Developing a building information modelling approach for 3D urban land administration in Iran: A case study in the city of Tehran. *Geocarto International*, 37(26), 12669–12688. https://doi.org/10.1080/10106049.2022.2071471.

El-Mekawy, M., Paasch, J. M., & Paulsson, J. (2015). Integration of legal aspects in 3D cadastral systems. *International Journal of E-Planning Research*, 4, 47–71.

El-Mekawy, M., Östman, A., & Shahzad, K. (2011). *Towards interoperating CityGML and IFC building models: A unified model-based approach*. In 5th 3D GeoInfo Conference. Lecture Notes in Geoinformation and Cartography Series. Heidelberg: Springer-Verlag.

Enemark, S. (2005). Understanding the land management paradigm. *In FIG Commission 7 Symposium on Innovative Technologies for Land Administration*, 19–25 June 2005, Madison, Wisconsin, USA. https://www.fig.net/organisation/council/council_2007-2010/council_members/enemark_papers/madison_2005.pdf.

Enemark, S. (2006). Sustainability and land administration systems. *In Proceedings of the Expert Group Meeting on Incorporating Sustainable Development Objectives into ICT Enabled Land Administration Systems*, 17–29. https://vbn.aau.dk/ws/files/2935555/SE_Melbourne_2005.pdf.

Enemark, S. (2009). *Managing rights, restrictions and responsibilities in land*. In GSDI-11 World Conference, Rotterdam, The Netherlands. https://vbn.aau.dk/ws/files/18418349/Enemark.pdf.

Enemark, S., & Sevatdal, H. (1999). *Cadastres, land information systems and planning*.

Enemark, S., McLaren, R., & Lemmen, C. H. J. (2015a). Fit-for-purpose land administration: Guiding principles for country implementation. GLTN Reference, Copenhagen, Denmark.

Enemark, S., McLaren, R., & Lemmen, C. H. J. (2015b). Fit-for-purpose land administration: Guiding principles. Global Land Tool Network (GLTN), Copenhagen, Denmark.

European Commission (EC). (2017a). New European Interoperability Framework: Promoting seamless services and data flows for European public administrations. https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf.

European Commission (EC). (2017b). Building information modelling (BIM) standardisation. JRC Technical Report. https://publications.jrc.ec.europa.eu/repository/handle/JRC109656.

European Commission (EC). (2022). *COMMISSION IMPLEMENTING REGULATION (EU) laying down a list of specific high-value datasets and the arrangements for their publication and re-use*. Document: C/2022/9562. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=PI_COM:C(2022)9562.

European Commission (EC). (2023a). Identification of data themes for the extensions of public sector high-value datasets – Final study. Publications Office of the European Union. https://data.europa.eu/doi/10.2759/739414.

European Commission (EC). (2023b). Technical guidelines for digital building logbooks: Guidelines to the member states on setting up and operationalising digital building logbooks under a common EU framework. Draft (unpublished).

European Parliament and Council. (2007). The directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an infrastructure for spatial information in the European Community (INSPIRE). *Official Journal of the European Union*, 108, 1.

FAO, UNECE, & FIG. (2022). Digital transformation and land administration – Sustainable practices from the UNECE region and beyond. FIG Publication No. 80. *Rome*, 88 pp. https://doi.org/10.4060/cc1908en.

FAO. (2012). *Voluntary guidelines on the responsible governance of tenure of land, fisheries and forests in the context of national food security (VGGT)*. http://www.fao.org/docrep/016/i2801e/i2801e.pdf.

FAO. (2020). *Open-source software for recording tenure rights*. https://www.fao.org/tenure/activities/administration/recording-of-rights/software/en/.

FAO. (2024). *SOLA Suite*. https://www.fao.org/tenure/sola-suite/about/en/.

FIEC. (2020). *FIEC position paper on the relationship between users and software companies/editors/service providers*. https://www.fiec.eu/application/files/4615/9281/3669/2020-02-24_FIEC_position_paper_on_the_relationship_between_users_and_software_companieseditorsservice_providers.pdf.

FIG. (2010). *The Social Tenure Domain Model: A pro-poor land tool (FIG Publication No.* 52). International Federation of Surveyors (FIG), Copenhagen, Denmark.

FIG. (2017). *Documentation of the 6th Land Administration Domain Workshop*. Delft, The Netherlands.

FIG. (2018a). *Proceedings of the 7th Land Administration Domain Workshop, Zagreb, Croatia*, 11–13 April 2018. Editors: Christiaan Lemmen, Peter van Oosterom & Elfriede Fendel. ISBN 978–87-92853–69-1. International Federation of Surveyors (FIG), Copenhagen, Denmark. https://wiki.tudelft.nl/bin/view/Research/ISO19152/LADM2018Workshop.

FIG. (2018b). Best practices 3D cadastres – extended version. In *P. van Oosterom* (Ed.), International Federation of Surveyors (FIG), Copenhagen, Denmark, March 2018. ISBN 978-87-92853-64-6, ISSN 2311-8423. http://www.fig.net/resources/publications/figpub/FIG_3DCad/FIG_3DCad-final.pdf.

FIG. (2019). *Proceedings of the 8th Land Administration Domain Model Workshop, Kuala Lumpur, Malaysia*, 1–3 October 2019. Editors: Peter van Oosterom, Christiaan Lemmen & Alias Abdul Rahman. International Federation of Surveyors (FIG), Copenhagen, Denmark. https://wiki.tudelft.nl/bin/view/Research/ISO19152/LADM2019Workshop.

FIG. (2021). *Proceedings of the 7th International FIG Workshop on 3D Cadastres, New York, USA*. Editors: Eftychia Kalogianni, Alias Abdul-Rahman & Peter van Oosterom. International Federation of Surveyors (FIG), Copenhagen, Denmark. https://doi.org/10.4233/uuid:398a642d-04e7–4c4d-b32b-398dbdc99b30.

FIG. (2022). *Proceedings of the 10th International FIG Workshop on the Land Administration Domain Model, Dubrovnik, Croatia*. Editors: Abdullah Kara, Rohan Bennett, Christiaan Lemmen & Peter van Oosterom. International Federation of Surveyors (FIG), Copenhagen, Denmark. https://doi.org/10.4233/uuid:446ad684-b9e0-48c2-81d9-85fc22537ddc.

FIG. (2023). *Proceedings of the 11th International FIG Workshop on LADM & 3D LA*, 11–13 October 2023, Gävle, Sweden. Editors: Peter van Oosterom & Jesper Paasch. International Federation of Surveyors (FIG), Copenhagen, Denmark. http://www.gdmc.nl/3DCadastres/workshop2023/programme/ProceedingsLADM_3DLA_2023.pdf.

FIG/World Bank. (2013). *Fit-for-purpose land administration*. International Federation of Surveyors (FIG), Copenhagen, Denmark.

Felus, Y., Barzani, S., Caine, A., Blumkine, N., & van Oosterom, P. J. M. (2014). Steps towards 3D cadastre and ISO 19152 (LADM) in Israel. *In Proceedings of the 4th International Workshop on 3D Cadastres*, 2014, Dubai, 391–409.

Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., Moorthy, I., Arias, R., Piera, J., Oliver, J. L., Masó, J., Penker, M., & Fritz, S. (2020). Mapping citizen science contributions to the UN sustainable development goals. *Sustainability Science*, 15, 1735–1751.

GLTN. (2017). *Social Tenure Domain Model – Bridging the land information gap*. UN-GGIM Expert Group on Land Administration and Management. https://gltn.net/download/gltn-partners-charter-february-2019/?wpdmdl=14793&refresh=6481a96bf0b5a1686219115.

GLTN. (2019). *Global Land Indicators Initiative*. http://mirror.gltn.net/index.php/land-tools/gltn-land-tools/global-land-indicators-initiative-glii.

GLTN/UN Habitat/Kadaster. (2015). *Fit-for-purpose land administration – Guiding principles*. UN-Habitat/GLTN, Nairobi, Kenya. https://www.fig.net/news/news_2016/2016_07_gltnguide/fit-for-purpose-land-adm-guidingprinciples-for-country-implementation.pdf.

Georgiadis, A. (2012). *Εγχειρίδιο Εμπραγμάτου Δικαίου* [Handbook of Property Law] *(2nd ed.)*. Sakkoulas Publications, Athens, Greece.

Gkeli, M., Potsiou, C., Soile, S., Vathiotis, G., & Cravariti, M. E. (2021). A BIM-IFC technical solution for 3D crowdsourced cadastral surveys based on LADM. *Earth*, 2(3), 605–621.

Glaner, M., & Weber, R. (2021). PPP with integer ambiguity resolution for GPS and Galileo using satellite products from different analysis centers. *GPS Solutions*, 25, Article 102. https://doi.org/10.1007/s10291-021-01140-z.

Govedarica, M., Radulovic, A., & Sladic, D. (2021). *Designing and implementing a LADM-based cadastral information system in Serbia, Montenegro and Republic of Srpska*. Land Use Policy.

Guler, D., van Oosterom, P. J. M., & Yomralioglu, T. (2022a). How to exploit BIM/IFC for 3D registration of ownership rights in multi-storey buildings: An evidence from Turkey. *Geocarto International*, 37(27

Guler, D., & Yomralioglu, T. (2022b). 3D description of condominium rights in Turkey: Improving the integrated model of LADM and IFC. In Proceedings of FIG Congress 2022.

Habitat III. (2016). *New Urban Agenda (NUA)*. http://habitat3.org/the-new-urban-agenda/.

Hajji, R., Yaagoubi, R., Meliana, I., Laafou, I., & Gholabzouri, A. E. (2021). Development of an integrated BIM–3D GIS approach for 3D cadastre in Morocco. *International Journal of Geo-Information*, 10(5), Article 351.

Hartenberger, U., Ostermeyer, Y., & Lützkendorf, T. (2021). *The building passport: A tool for capturing and managing whole life data and information in construction and real estate*. Practical guideline. Global Alliance for Buildings and Construction (GABC). https://globalabc.org/sites/default/files/2021-09/GABC_The-Building-Passport_FINAL.pdf.

Hespanha, J. P. (2012). *Development methodology for an integrated legal cadastre: Deriving Portugal country model from the Land Administration Domain Model*. PhD thesis, Delft University of Technology, Delft, The Netherlands.

Hevner, A., & Chatterjee, S. (2010). Design science research in information systems. *In Design research in information systems*, 9–22. Springer, Boston, MA.

INSPIRE. (2012). *Data Specification on Land Use – Draft Guidelines*. D2.8.III.4. INSPIRE Thematic Working Group Land Use.

Indrajit, A. (2021). *4D open spatial information infrastructure: Participatory urban plan monitoring in Indonesian cities*. A+BE | Architecture and the Built Environment.

Indrajit, A., van Loenen, B., Ploeger, H., & van Oosterom, P. J. M. (2020). Developing a spatial planning information package in ISO 19152 Land Administration Domain Model. *Land Use Policy*, 98, 104111. https://doi.org/10.1016/j.landusepol.2019.104111.

Indrajit, A., van Loenen, B., Suprajaka, Jaya, V. E., Ploeger, H., Lemmen, C. H. J., & van Oosterom, P. J. M. (2021). Implementation of the spatial plan information package for improving ease of doing business in Indonesian cities. *Land Use Policy*, 105, 105338. https://doi.org/10.1016/j.landusepol.2021.105338.

Intergovernmental Committee on Surveying and Mapping (ICSM). (2023). *3D cadastre survey data model and exchange specification*. https://icsm-au.github.io/3D-csdm/.

International Hydrographic Organisation (IHO). (2019). *S-121 Maritime Limits and Boundaries (Edition 1*.0.0). https://registry.iho.int/productspec/%20view.do?idx=177&product_ID=S-121&statusS=5&domainS=ALL&category=product_ID&searchValue=.

International Hydrographic Organization (IHO). (2018). *S-100 Universal Hydrographic Data Model (Edition 4*.0.0). https://iho.int/uploads/user/pubs/standards/s-100/S-100_Ed%204.0.0_Clean_17122018.pdf.

International Organisation for Standardisation (ISO). (2004). *ISO 19106:2004, Geographic information — Profiles*. https://www.iso.org/standard/26011.html.

International Organisation for Standardisation (ISO). (2011). *ISO 19156:2011, Observations and Measurement Standard*.

International Organisation for Standardisation (ISO). (2012). *ISO 19152:2012, Land Administration Domain Model (LADM)*. https://www.iso.org/standard/51206.html.

International Organisation for Standardisation (ISO). (2013). *ISO 19157, Geographic Information — Data Quality*.

International Organisation for Standardisation (ISO). (2015). *ISO 19109:2015, Geographic information — Rules for application schema*. https://www.iso.org/standard/59193.html?browse=tc.

International Organisation for Standardisation (ISO). (2016a). ISO 19110:2016, Geographic information — Methodology for feature cataloguing.

International Organisation for Standardisation (ISO). (2016b). ISO 29481–1:2016 – Building Information Models – Information Delivery Manual – Part 1: Methodology and Format.

International Organisation for Standardisation (ISO). (2021). *ISO 19126:2021, Geographic information — Feature concept dictionaries and registers*.

International Organisation for Standardisation (ISO). (2023). *ISO 19156:2023, Geographic information — Observations & Measurements*.

International Organisation for Standardisation/Technical Committee 211 (ISO/TC211). (2023). *Geographic information – Input to EU data spaces (Report ISO/TC 211 N 5971)*. https://committee.iso.org/files/live/users/fh/aj/aj/tc211contributor%40iso.org/files/EU/ISO-TC211_N5971.pdf.

International Organisation for Standardisation (ISO). (2024). *ISO 16739-1:2024 – Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data schema*. https://www.iso.org/standard/84123.html.

International Organisation for Standardisation (ISO). (2024a). ISO 19152-1:2024, Geographic information — Land Administration Domain Model (LADM) Part 1: Generic conceptual model. https://www.iso.org/standard/81263.html.
International Organisation for Standardisation (ISO). (2024b). ISO 19152-3:2024, Geographic information — Land Administration Domain Model (LADM) Part 3: Marine georegulation. https://www.iso.org/standard/81265.html.
International Organisation for Standardisation (ISO). (2025a). ISO 19152-2:2025, Geographic information — Land Administration Domain Model (LADM) Part 2: Land registration. https://www.iso.org/standard/81264.html.
International Organisation for Standardisation (ISO). (2025b). ISO 19152-4:2025, Geographic information — Land Administration Domain Model (LADM) Part 4: Valuation information. https://www.iso.org/standard/81266.html.
International Organisation for Standardisation (ISO). (2025c). ISO 19152-5:2025, Geographic information — Land Administration Domain Model (LADM) Part 5: Spatial plan information. https://www.iso.org/standard/81267.html
Janečka, K., & Souček, P. (2016). Country profile for the cadastre of the Czech Republic based on LADM. *In Proceedings of the 5th International FIG 3D Cadastre Workshop, Athens, Greece*, 18–20 October 2016.
Janečka, K., & Souček, P. (2017). A country profile of the Czech Republic based on an LADM for the development of a 3D Cadastre. *ISPRS International Journal of Geo-Information*, 6(5), Article 143. https://doi.org/10.3390/ijgi6050143.
Janečka, K., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., & Govedarica, M. (2018). *Lessons learned from the creation of the LADM based country profiles.* In Proceedings of the 7th Land Administration Domain Model Workshop, Zagreb, Croatia.
Jenni, L., Lopez, A. G., Ziegler, S., & Perez, V. M. B. (2017). Development and employment of an LADM implementing toolkit in Colombia. *In Proceedings of the 2017 World Bank Conference on Land and Poverty, Washington, DC, USA*, 20–24 March 2017.
Jeong, D. H., Jang, B. B., Lee, J. Y., Hong, S. I., van Oosterom, P. J. M., de Zeeuw, K., Stoter, J., Lemmen, C. H. J., & Zevenbergen, J. (2012). *Initial design of an LADM-based 3D cadastre – Case study from Korea.* In Proceedings of the 3rd International Workshop on 3D Cadastres, Shenzhen, pp. 159–184.
Johannesson, P., & Perjons, E. (2014). *An introduction to design science.* Springer Publishing Company, Incorporated.
KOGIS. (2006). *INTERLIS 2.*3 Reference Manual. Coordination, Geo-Information and Services (COGIS), Swiss Federal Office of Topography: Wabern, Switzerland.
Kalantari, M., Dinsmore, K., Urban-Karr, J., & Rajabifard, A. (2015). A roadmap to adopt the Land Administration Domain Model in cadastral information systems. *Land Use Policy*, 49, 552–564.
Kalogianni, E., Dimopoulou, E., & van Oosterom, P. J. M. (2017). A 3D LADM prototype implementation in INTERLIS. In *A. Abdul-Rahman* (Ed.), Advances in 3D Geoinformation (pp. 137–157). Lecture Notes in Geoinformation and Cartography. Springer. https://doi.org/10.1007/978-3-319-25691-7_8.
Kalogianni, E., Dimopoulou, E., & van Oosterom, P. J. M. (2018). 3D cadastre and LADM – Needs and expectations towards LADM revision. *7th International FIG Workshop on the Land Administration Domain Model*, 11–13 April 2018, Zagreb, Croatia.
Kalogianni, E., Dimopoulou, E., Gruler, H. C., Stubkjær, E., Lemmen, C. H. J., & van Oosterom, P. J. M. (2021b). Developing the refined survey model for the LADM revision supporting interoperability with LandInfra. In Proceedings of FIG Working Week 2021, p. 27. ISBN: 978-87-92853-65-3.
Kalogianni, E., Dimopoulou, E., Gruler, H.-C., Stubkjær, E., Morales, J., Lemmen, C.H.J., van Oosterom, P.J.M. (2024). Refining the survey model of the LADM ISO 19152–2: Land registration. *Land Use Policy*, 141, 107125. https://doi.org/10.1016/j.landusepol.2024.107125.
Kalogianni, E., Dimopoulou, E., Quak, W., & van Oosterom, P. J. M. (2016). Formalising implementable constraints in the INTERLIS language for modelling legal 3D RRR spaces and 3D physical objects. *In Proceedings of the 5th International FIG 3D Cadastre Workshop, Athens, Greece*, 18–20 October 2016, pp. 137–157.
Kalogianni, E., Dimopoulou, E., Thompson, R. J., Lemmen, C. H. J., Ying, S., & van Oosterom, P. J. M. (2020b). Development of 3D spatial profiles to support the full lifecycle of 3D objects. *Land Use Policy*, 98, 104177.

Kalogianni, E., Gruler, H. C., Bar-Maor, A., Harold, B., Lemmon, T., Lemmen, C. H. J., & van Oosterom, P. J. M. (2022b). Investigating the requirements for the ISO 19152 LADM survey encodings. In Proceedings of the 10th International FIG Workshop on the Land Administration Domain Model, pp. 53–66.

Kalogianni, E., Janečka, K., Kalantari, M., Dimopoulou, E., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., Govedarica, M., Lemmen, C. H. J., & van Oosterom, P. J. M. (2021a). Methodology for the development of LADM country profiles. *Land Use Policy*, 105, 105380. https://doi.org/10.1016/j.landusepol.2021.105380.

Kalogianni, E., Kara, A., Beck, A., Paasch, J. M., Zevenbergen, J., Dimopoulou, E., Kitsakis, D., van Oosterom, P. J. M., & Lemmen, C. H. J. (2022a). Refining the legal land administration-related aspects in LADM. *In Proceedings of the 10th International FIG Workshop on the Land Administration Domain Model*, 31 March – 2 April 2022, Dubrovnik, Croatia.

Kalogianni, E., van Oosterom, P. J. M., Dimopoulou, E., & Lemmen, C. H. J. (2020a). 3D land administration: A review and a future vision in the context of the spatial development lifecycle. *International Journal of Geo-Information*, 9, Article 107.

Kalogianni, E., van Oosterom, P.J.M., Schmitz, M., Capua, R., Verbree, E., Dimopoulou, E., Gruler, H.C., Stubkj, E., Morales, J. and Lemmen, C.H.J. (2023). Galileo High Accuracy Services support through ISO 19162 LADM Edition II. In Proceedings: FIG Working Week 2023 - Protecting Our World, Conquering New Frontiers. *Orlando, Florida, USA*, 28 May–1 June 2023.

Kara, A., Chen, M., Oosterom, P.J.M., Lemmen, C.H.J. (2024b). Monitoring Indicators of International Guidance Documents and Frameworks through LADM. In Proceedings: 12th International FIG Land Administration Domain Model & 3D Land Administration Workshop. 24-26 September 2024, Kuching, Malaysia.

Kara, A., Lemmen, C.H.J., Kalogianni, E., van Oosterom, P.J.M. (2023a). Requirements-based Design of the LADM Edition II. In Proceedings: 11th International FIG Land Administration Domain Model / 3D Land Administration Workshop. 11-13 October 2023, Gävle, Sweden.

Kara, A., Lemmen, C.H.J., Oosterom, P.J.M., Kalogianni, E., Alattas, A., Indrajit, A. (2024a). Design of the new structure and capabilities of LADM Edition II including 3D aspects. *Land Use Policy*, 137, 107003. doi: https://doi.org/10.1016/j.landusepol.2023.107003.

Kara, A., Oosterom, P.J.M., Kathmaann, R., Lemmen, C.H.J. (2023b). Visualisation and dissemination of 3D valuation units and groups – An LADM valuation information compliant prototype. *Land Use Policy*, 132, 106829. Available online: https://www.gdmc.nl/publications/2023/LUP_3D_ValuationUnitsGroupsLADM.pdf.

Kara, A., Rowland, A., van Oosterom, P.J.M., Stubkjaer, E., Çağdaş, V., Folmer, E., Lemmen, C.H.J., Wilko, Q. and Meggiolaro, L. (2022). Formalisation of code lists and their values–The case of ISO 19152 Land Administration Domain Model. In *Proceedings: 10th Land Administration Domain Model Workshop* (pp. 333-354). International Federation of Surveyors. Available online: https://research.tudelft.nl/files/117223010/LADM2022_paper_G3.pdf.

Kara, A., Unger, E.M., van Oosterom, P.J.M., Lemmen, C.H.J. (2023c). LADM's Links with International Standards, Guidelines and Frameworks. In Proceedings: 11th International FIG Land Administration Domain Model / 3D Land Administration Workshop. 11-13 October 2023, Gävle, Sweden.

Kara, A., van Oosterom, P.J.M., Çağdaş, V., Işıkdağ, Ü., Lemmen, C.H.J. (2020). 3-Dimensional data research for property valuation in the context of the LADM valuation information model. *Land Use Policy Volume 98*, 104179. Available online: https://doi.org/10.1016/j.landusepol.2019.104179.

Kara, A., Çağdaş, V., Işıkdağ, Ü, van Oosterom, P.J.M., Lemmen, C.H.J., Stubkjaer, E. (2021). The LADM valuation information model and its application to the Turkey case. *Land Use Policy, Volume 104*, 105307. Available online: https://doi.org/10.1016/j.landusepol.2021.105307.

Kara, A., Çağdaş, V., Işıkdağ, Ü., van Oosterom, P. J. M., Lemmen, C. H. J., Stubkjær, E. (2018b). The LADM Valuation Information Model based on INTERLIS. 285-302. Paper presented at 7th International FIG Workshop on the Land Administration Domain Model 2018, Zagreb, Croatia. Available online: https://doi.org/10.4233/uuid:ad1cd0eb-2732-4ae8-8f54-5064813b7439.

Kara, A., Çağdaş, V., Lemmen, C.H.J., Işıkdağ, Ü., van Oosterom, P.J.M., Stubkjær, E. (2018a). Supporting fiscal aspect of land administration through a LADM-based valuation information model. In Proceedings: Land Governance in an interconnected World. Available online: https://vbn.aau.dk/ws/files/273445419/07_08_Kara_439_paper.pdf.

Karki, S., Thompson, R., McDougall, K., Cumerford, N. van Oosterom, P.J.M. (2011). ISO Land Administration Domain Model and LandXML in the Development of Digital Survey Plan Lodgement for 3D Cadastre in Australia. *In Proceedings: 2nd International Workshop on 3D Cadastres*, 2011, Delft, pp. 65-84.
Kaufmann, J., and Steudler, D. (1998). Cadastre 2014: A vision for a future cadastral system. In *Lemmen, C.H.J., FIG Commission 7. The International Federation of Surveyors* (FIG).
Kavisha, K. (2020). *Modelling and managing massive 3D data of the built environment*. Ph.D. Thesis, Delft University of Technology, Deft, The Netherlands.
Kelm, K., Antos, S., McLaren, R. (2021). Applying the FFP Approach to Wider Land Management Functions. *Land 2021*, 10, 723.
Kim, S., Kim, J., Jung, J., & Heo, J. (2015). *Development of a 3D underground cadastral system with indoor mapping for as-built BIM: The case study of Gangnam Subway Station in Korea*. Sensors15.
Kitsakis, D. (2019). *Legal requirements for real property stratification*. PhD thesis, National Technical University of Athens, Athens, Greece.
Kitsakis, D., & Dimopoulou, E. (2016). Possibilities of integrating public law restrictions to 3D cadastres. In *P. van Oosterom, E. Dimopoulou, & E. M. Fendel* (Eds.), 5th International FIG 3D Cadastre Workshop (pp. 25–46). Athens, Greece.
Kitsakis, D., & Dimopoulou, E. (2017). Addressing public law restrictions within a 3D cadastral context. *ISPRS International Journal of Geo-Information*, 6(7), 182. https://doi.org/10.3390/ijgi6070182.
Kitsakis, D., Kalogianni, E., & Dimopoulou, E. (*2022). Public law restrictions in the context of 3D land administration—Review on legal and technical approaches*. Land11(1).
Kitsakis, D., Kalogianni, E., Dimopoulou, E., Zevenbergen, J., & van Oosterom, P. J. M. (2021). Modelling 3D legal spaces of public law restrictions within the context of LADM revision. *7th International FIG 3D Cadastre Workshop*, 11–13 October, New York, USA (online). https://doi.org/10.4233/uuid:a116493a-2cb6-4781-b2c4-3f2c94611ad8.
Kort og Matrikelstyrelsen. (2006). *Property formation in the Nordic countries - Denmark*. Danish Geodata Agency. https://gst.dk/media/2916021/propertyformationinthenordiccountries.pdf.
Kuria, D., Ngigi, M., Gikwa, C., Mundia, C., & Macharia, M. (2016). A web-based pilot implementation of the Africanized Land Administration Domain Model for Kenya—A case study of Nyeri County. *Journal of Geographic Information System*, 8, 171–183. http://dx.doi.org/10.4236/jgis.2016.82016.
Land Equity International/Millennium Challenge Corporation (LEI/MCC). (2020). *Land administration information and transaction systems – Final state of practice paper*. https://www.landequity.com.au/wp-content/uploads/2020/11/LAND-INFORMATION-AND-TRANSACTION-SYSTEMS-STATE-OF-PRACTICE-FINAL.pdf.
LandXML. (2016). *LandXML - 1*.2. http://www.landxml.org/About.aspx.
Lemmen C.H.J., van Oosterom P.J.M. (2003). *3D Cadastres (Editorial), Computers, Environment and Urban Systems*, 27(4), 337–343.
Lemmen, C.H.J. (2010). *The Social Tenure Domain Model*. FIG Publication 52, FIG Office, Copenhagen, Denmark.
Lemmen, C.H.J. (2012). *A Domain Model for Land Administration*. Ph.D. thesis, Delft University of Technology, Delft, The Netherlands.
Lemmen, C.H.J., da Silva Mano, A., Chipofya, M. (2021). LADM in the Classroom – Making the Land Administration Domain Model Accessible. *In FIG Congress 2022 - Volunteering for the future - Geospatial excellence for a better living, Warsaw, Poland*, 11–15 September 2022.
Lemmen, C.H.J., van Oosterom, P.J.M., Bennett, R. (2015a). The Land Administration Domain Model. *Land Use Policy*, 49, 535–545.
Lemmen, C.H.J., van Oosterom, P.J.M., Kalantari, M., Unger, E.M., Teo, C.H., de Zeeuw, K. (2017). Further Standardisation in Land Administration. *World Bank Conference on Land and Poverty, Washington, DC, March 20–24*, 2017.
Lemmen, C.H.J., van Oosterom, P.J.M., Kalogianni, E. (2020). LADM: The next phase. *GEO: connexion*, 19(3), 20–21.
Lemmen, C.H.J., van Oosterom, P.J.M., Uitermark, H., de Zeeuw, K. (2013). Land Administration Domain Model is an ISO standard now. *Annual World Bank Conference on Land and Poverty, Washington, DC, April 8–11*, 2013.

Liu, C., Zhu, H., Li, L., Ma, J., Li, F. (2023). *BIM/IFC-based 3D spatial model for condominium ownership: a case study of China.* Geo-spatial Information Science. https://doi.org/10.1080/10095020.2023.2246518.

Mao, P. (2024). *A digital twin based on Land Administration.* Master's thesis, Delft University of Technology, Delft, The Netherlands.

Mao, P., van Oosterom, P.J.M., Rafiee, A. (2024). *A digital twin based on Land Administration.* In 12th International FIG Land Administration Domain Model & 3D Land Administration Workshop.

March, S.T., & Smith, G.F. (1995). Design and natural science research on information technology. *Decision Support Systems*, 15(4).

Mađer, M., Matijevic, H., Roić, M. (2015). Analysis of possibilities for linking Land Registers and Other Official Registers in the Republic of Croatia based on LADM. *Land Use Policy*, 49, 606–616.

Meulmeester, R.W.E. (2019). *BIM Legal.* Proposal for Defining Legal Spaces for Apartment Rights in the Dutch Cadastre Using the IFC Data Model. Master's thesis, Delft University of Technology, Delft, The Netherlands.

Morales Guarin, J.M., Lemmen, C.H.J., de By, R., Molendijk, M., Oosterbroek, E.-P., Ortiz Davila, A.E. (2019). *On the design of a modern and generic approach to land registration: The Colombia experience.* In 8th Land Administration Domain Model Workshop 2019, Kuala Lumpur, Malaysia. https://doi.org/10.4233/uuid:39072a6f-1ca8-4897-95bc-48f0f422ef38.

Morales, J.G., Lemmen, C., By, R.A., Dávila, A.E., Molendijk, M. (2021). Designing all-inclusive land administration systems: A case study from Colombia. *Land Use Policy*, 109, 105617.

Morgenthaler (2020). Colombia uses Collector to support land administration. *ArcGIS Blog*, 26 May 2020. https://www.esri.com/arcgis-blog/products/collector/field-mobility/colombia-uses-collector-for-arcgis-to-support-land-administration/.

Mulyadi, M., & Faizel, A. (2022). Web-based 3D cadastre's data visualization in Indonesia: Challenges and opportunity. *In FIG Congress 2022 – Volunteering for the future – Geospatial excellence for a better living, Warsaw, Poland*, 11–15 September 2022.

Murgante, B., Donato, P. D., Berardi, L., Salvemini, M., & Vico, F. (2011). Plan4all: European network of best practices for interoperability of spatial planning information. *2011 International Conference on Computational Science and Its Applications*, 286–289. https://doi.org/10.1109/ICCSA.2011.45.

Müller, H. L., & Seifert, M. (2019). Blockchain, a feasible technology for land administration. *In FIG Working Week: Geospatial information for a smarter life and environmental resilience, Hanoi*, 22–26 April 2019.

Navratil, G. (2012). Combining 3D cadastre and public law – An Austrian perspective. *In 3rd International Workshop on 3D Cadastres, Shenzhen, China*, 61–72.

Object Management Group (OMG). (2011). *Business Process Model and Notation (BPMN), Version 2*.0. http://www.omg.org/spec/BPMN/2.0.

Okembo, C., Lemmen, C., Kuria, D., & Zevenbergen, J. (2023). Land Administration Domain Model profile for Kenya. *Survey Review*, 1–25.

Oldfield, J., Bergs, R., van Oosterom, P. J. M., Krijnen, T. F., & Galano, M. M. (2018). 3D cadastral lifecycle: An information delivery manual ISO 29481 for 3D data extraction from the building permit application process. In *C. Lemmen, P. van Oosterom, & E. Fendel* (Eds.), Proceedings of the 7th Land Administration Domain Model Workshop (pp. 153–170). International Federation of Surveyors (FIG).

Oldfield, J., van Oosterom, P. J. M., Beetz, J., & Krijnen, T. F. (2017). Working with open BIM standards to source legal spaces for a 3D cadastre. *ISPRS International Journal of Geo-Information*, 6, 351. https://doi.org/10.3390/ijgi6110351.

Olfat, H., Atazadeh, B., Shojaei, D., & Rajabifard, A. (2019). The feasibility of a BIM-driven approach to support building subdivision workflows: Case study of Victoria, Australia. *ISPRS International Journal of Geo-Information*, 8, 499.

Open Geospatial Consortium (OGC) & buildingSMART International (2020). *Built environment data standards and their integration: an analysis of IFC, CityGML and LandInfra.* OGC Document 19-091r1. bSI TR1012.

Open Geospatial Consortium (OGC) (2024b). Urban Digital Twins: Integrating Infrastructure, natural environment and people. Discussion Paper. OGC Document: 24-025.

Open Geospatial Consortium (OGC) (2024c). 128th Member Meeting GEO-BIM for the Built Environment, Delft, The Netherlands.

Open Geospatial Consortium (OGC). (2016). *Land and Infrastructure Conceptual Model Standard (Doc. No. 15-111r1).*

Open Geospatial Consortium (OGC). (2017). *OGC InfraGML 1*.0: Part 0 – LandInfra Core - Encoding Standard.
Open Geospatial Consortium (OGC). (2018). *OGC White Paper on Land Administration*. https://docs.ogc.org/wp/18-008r1/18-008r1.html.
Open Geospatial Consortium (OGC). (2019). *OGC White Paper on Land Administration*.
Open Geospatial Consortium (OGC). (2024a). Land Administration Domain Model Standards Working Group Charter.
Open Geospatial Consortium. (2023). *OGC Features and Geometries JSON – Part 1: Core*. https://docs.ogc.org/DRAFTS/21-045.html.
Open and Agile Smart Cities (OASC). (2024). *OASC MIMs*. https://mims.oascities.org.
Paasch, J.M. (2012). *Standardization of Real Property Rights and Public Regulations: The Legal Cadastral Domain Model*. KTH Royal Institute of Technology, Stockholm, Sweden.
Paasch, J.M., Paulsson, J. (2023). Trends in 3D cadastre – A literature survey. *Land Use Policy*, 131(C).
Paasch, J.M., van Oosterom, P.J.M., Lemmen, C.H.J., Paulsson, J. (2015) Further modelling of LADM's rights, restrictions and responsibilities (RRRs). *Land use policy*, 49(2015), 680-689.
Peffers, K., Tuunanen, T., Rothenberger, M.A., and Chatterjee, S. (2007). A Design Science Research Methodology for Information Systems Research. *Journal of Management Information Systems*, 24 (3).
Petronijević, M., Višnjevac, N., Praščević, N., Bajat, B. (2021). The extension of IFC for supporting 3D cadastre LADM geometry. ISPRS Int. J. Geo-Inf. *2021,10*, 297. Doi: 10.3390/ijgi10050297.
Polat, Z.A., Alkan, M. (2018a). Design and implementation of a LADM-based external archive data model for land registry and cadastre transactions in Turkey: A case study of municipality. *Land Use Policy*, 77(C), 249-266.
Pouliot, J., Vasseur, M., & Boubehrezh, A. (2013). *How the ISO 19152 Land Administration Domain Model performs in the comparison of cadastral systems: A case study of condominium/co-ownership in Quebec (Canada) and Alsace Moselle (France)*. Comput. Environ. Urban Syst., 40, 68–78.
Radulovic, A., Sladic, D., Govedarica, M., Ristic, A.V., Jovanovic, D. (2019). *LADM Based Utility Network Cadastre in Serbia*. ISPRS Int. J. Geo Inf., 8, 206.
Ramlakhan, R., Kalogianni, E., van Oosterom, P.J.M., Atazadeh, B. (2023). Modelling the legal spaces of 3D underground objects in 3D Land Administration Systems. *Land Use Policy*, 127, 106537.
Reid, A. (*2019). A new register for Scotland.*
Riekkinen, K., Toivonen, S., Krigsholm, P., Hiironen, J., Kolis, K. (2016). Future themes in the operational environment of the Finnish cadastral system. *Land Use Policy*, 57, 702-708.
Roes, R., Vos, J., Smudde, D., Bolhaar, J.P., Boellaard, L. (2023). *BIM Legal the standard for the 3D transformation of legal certainty for apartment law*. In proceedings: FIG Commission 7 Annual Meeting, Digital Transformation for Responsible Land Administration. Deventer, The Netherlands.
Saeidian, B. (2023). *3D Data Modelling for Underground Land Administration*. PhD Dissertation. The University of Melbourne.
Saeidian, B., Rajabifard, A., Atazadeh, B., Kalantari, M. (2021). Underground Land Administration from 2D to 3D: Critical Challenges and Future Research Directions. *Land*, 10, 1101. https://doi.org/10.3390/land10101101.
Saeidian, B., Rajabifard, A., Atazadeh, B., Kalantari, M. (2022). *Development of an LADM-based Conceptual Data Model for 3D Underground Land Administration in Victoria*. In proceedings: 10th International FIG workshop on the Land Administration Domain Model. 31 March - 2 April 2022, Dubrovnik, Croatia.
Saeidian, B., Rajabifard, A., Atazadeh, B., Kalantari, M. (2023). A semantic 3D city model for underground land administration: Development and implementation of an ADE for CityGML 3.0. *Tunnelling and underground space technology*, 140, 105267.
Scott, G., Rajabifard, A. (2017). Sustainable development and geospatial information: a strategic framework for integrating a global policy agenda into national geospatial capabilities. *Geo-Spatial Information Science*, 20(2), 59–76.
Sein, M., Henfridsson, O., Purao, S., Rossi, M., Lindgren, R. (2011). *Action design research*. MIS Q., 35, 37-56.
Shahidinejad, J., Kalantari, M., Rajabifard, A. (2024). *3D Cadastral Database Systems—A Systematic Literature Review*. ISPRS Int. J. Geo-Inf., 13, 30.
Shiu, W., Mitchell, D., Muller, H., Mahmud, M.R., Roman, D., Henriques, M.J., Paez, D., Louwsma, M., Elder, B., Muse, A. (2021). *Key Global and Technology Drivers Impacting Surveying*. GIM International.

Shnaidman, A., van Oosterom, P.J.M., Rahman, A.A., Karki, S., Lemmen, C.H.J., Ploeger, H. (2019). Analysis of the Third FIG 3D Cadastres Questionnaire: Status in 2018 and Expectations for 2022. *In Proceedings of the FIG WW 2019, Hanoi, Vietnam*, 22–26 April 2019.

Shojaei, D. (2014). *3D cadastral visualisation: understanding users' requirements, Ph*.D. Thesis, University of Melbourne, Australia.

Simon, H. (1996) *The Sciences of Artificial*, 3rd ed., MIT Press, Cambridge, MA.

Simsek, C.N., Uzun, B. (2021). Building Information Modelling (BIM) for property valuation: A new approach for Turkish Condominium Ownership. *Survey Review*, 54, 187 - 208.

Sladić, D., Radulović, A., Govedarica, M. (2018). Processes in cadastre: process model for Serbian 3D cadastre. *In Proceedings: 6th International FIG 3D Cadastre Workshop*, 2-4 October, Delft, The Netherlands (2018), pp. 39-56.

Sladić, D., Radulović, A., Govedarica, M. (2020). Development of process model for Serbian cadastre. *Land Use Policy*, 98(C).

Smith, K. (2019). The Role of LADM in Configurable Geographic Information Systems. *In Proceedings: 8th International FIG workshop on the Land Administration Domain Model*, 1-3 October 2019, Kuala Lumpur, Malaysia.

Steudler, D. (Ed) (2014). *Cadastre 2014 and Beyond*. Publication No. 61. International Federation of Surveyors (FIG). ISBN 978-87-92853-13-4.

Steudler, D., Rajabifard, A., Williamson, I. P. (2004). Evaluation of land administration systems. *Land Use Policy*, 21(4), 371-380.

Stoter, J. (2004). *3D Cadastre*. Ph.D. Thesis, Delft University of Technology, Deft, The Netherlands.

Stoter, J., Diakité, A., Reuvers, M., Smudde, D., Vos, J., Roes, R., van der Vaart, J., Hakim, A., El Yamani, S. (2024). *BIM Legal: Implementation of a standard for Cadastral Registration of Apartment Complexes in 3D, Int*. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-4/W11-2024, 111–120, https://doi.org/10.5194/isprs-archives-XLVIII-4-W11-2024-111-2024, 2024.

Stoter, J.E., van Oosterom, P.J.M. (2006). *3D Cadastre in an International Context: Legal, Organizational, and Technological Aspects*.

Stubkjær, E., Paasch, J.M., Çağdaş, V., van Oosterom, P.J.M., Simmons, S., Paulsson, J., Lemmen, C.H.J. (2018). International Code List Management - The Case of Land Administration, In: Proceedings of the 7th Land Administration Domain Model Workshop, Zagreb, pp. *22*, 2018.

Stubkjær, E., Çağdaş, V. (2021) Alignment of standards through semantic tools–The case of land administration. *Land Use Policy*, 104, 105381.

Sun (2022). *Integration of BIM and 3D GIS for sustainable cadastre*. Ph.D. Thesis, KTH Royal Institute of Technology. Stockholm, Sweden.

Sun, J., Paasch, J., Paulsson, J., Tarandi, V., Harrie, L. (2023). *A BIM-based approach to design a lifecycle 3D property formation process A Swedish case study*. Land Use Policy. 131. 10.1016/j.landusepol.2023.106712.

Sun, J., Paulsson, J., Harrie, L., Eriksson, K., Paasch, J. M., Tarandi, V. (2022). *BIM-based 3D Cadastral Management, Stockholm*.

Thompson, R., van Oosterom, P.J.M. (2021). Bi-temporal foundation for LADM v2: fusing event and state-based modelling of land administration data 2D and 3D. *Land Use Policy 102*, 105246.

Thompson, R.J., Kalogianni, E., van Oosterom, P.J.M. (2023). *Analysing 3D Land Administration developments and plans from 2010 to 2026*. In Proceedings: 11th International FIG Workshop on LADM/3D LA, pp. 119-132, part of ISBN: 978-87-93914-09-4.

Thompson, R.J.P., van Oosterom, P.J.M., Karki, S. (2019). *Towards an implementable data schema for 4D/5D cadastre including Bi-temporal support*. In: FIG Working Week 2019. Hanoi, Vietnam. Available online:.

Thompson, R.J.P., van Oosterom, P.J.M., Karki, S., Cowie, B. (2015). *A Taxonomy of Spatial Units in a Mixed 2D and 3D Cadastral Database*. FIG Working Week 2015. Sofia, Bulgaria.

Thompson, R.P., van Oosterom, P.J.M., Soon, K.H. (2016b). Mixed 2D and 3D survey plans with topological encodings. In: Proceedings of the 5th International FIG 3D Cadastre Workshop. Athens, Greece, October 18-20.

Thompson, R.P., van Oosterom, P.J.M., Soon, K.H. (2017). LandXML Encoding of Mixed 2D and 3D Survey Plans with Multi-Level Topology. ISPRS Int. J. Geo-Inf. *2017*, 6(6), 171; doi:10.3390/ijgi6060171.

Thompson, R.P., van Oosterom, P.J.M., Soon, K.H. Priebbenow, R. (2016a). A Conceptual Model supporting a range of 3D parcel representations through all stages: Data Capture, Transfer and Storage. *In: FIG Working Week 2016 – Recovery from Disaster, Christchurch, New Zealand, May 2-6*, 2016.
UN-GGIM (2016). *Addis Ababa Declaration on Geospatial Information Management towards Good Land Governance for the 2030 Agenda.*
UN-GGIM (2019). *Fundamental Geospatial Data Themes.*
UN-GGIM (2020). *Framework for Effective Land Administration: A reference for developing, reforming, renewing, strengthening, modernizing, and monitoring land administration (FELA).*
UN-Habitat (2003). *Handbook on best practices, security of tenure and access to land.* Nairobi: United Nations Human Settlements Programme.
UN-Habitat/ GLTN (2008). *Secure Land Rights for All.* Nairobi: United Nations Human Settlements Programme.
UN-Habitat/ GLTN (2013). *Introduction to STDM - In the Context of Participatory Enumeration and Settlement Upgrading, Version 0.*9.5.
UN-Habitat/ GLTN (2023). *Guidance Note on the Application of the Social Tenure Domain Model in Syria.* Nairobi, United Nations Human Settlements Programme (UN-HABITAT).
UN-Habitat/ GLTN/ Kadaster (2016). *Fit-for-purpose land administration: guiding principles for country implementation.* Nairobi, United Nations Human Settlements Programme (UN-HABITAT).
UNECE (1996). *Land administration guidelines – with special reference to countries in transition.* Unites Nations/ Economic Commission for Europe.
UNECE (2021). *Scenario Study on Future Land Administration in the UNECE Region.* United Nations/ Economic Commission for Europe, e-ISBN: 9789210011204.
UNFPA (2007) State of the World Population 2007, Unleashing the Potential of Urban Growth.
UNGGIM (2019a). Fundamental Geospatial Data Themes.
UNGGIM (2019b). The United Nations Initiative on Global Geospatial Information Management (UN-GGIM).
UNGGIM (2019c). Framework for Effective Land Administration.
USAGE Deliverable 3.2–Data Space Prototype and Report–First Version (*2024).*
USAID (2016). *Evaluation, Research and Communication – Mobile Application to Secure Tenure (MAST).* Lessons learned report.
Unger, E.M., Bennett, R., Lemmen, C.H.J., Zevenbergen, J. (2021). LADM for sustainable development: An exploratory study on the application of domain-specific data models to support the SDGs. *Land Use Policy*, 108, 105499.
Unger, E.M., Bennett, R., Lemmen, C.H.J., Zevenbergen, J.A., Dijkstra, P., de Zeeuw, K. (2019). LADM based models for sustainable development LA-DRM for disaster prone areas and communities (an example for SDG 1 and SDG 13). *In Proceedings: 8th International FIG Workshop on the Land Administration Domain Model*, 1-3 October 2019, Kuala Lumpur, Malaysia.
Unger, E.M., Bennett, R., Lemmen, C.H.J., de Zeeuw, K., Zevenbergen, J.A., Teo, C., Crompvoets, J. (2020). Global policy transfer for land administration and disaster risk management. *Land Use Policy*, 99, 104834.
Unger, E.M., Gitau, J. (2023b). The Social Tenure Domain Model (STDM). Keynote Presentation. In: 11th International FOG Workshop on LADM & 3D LA.
Unger, E.M., Lemmen, C.H.J., Bennett, R. (2023a). Women's access to land and the Land Administration Domain Model (LADM): requirements, modelling and assessment. *Land Use Policy 126*, 106538.
United Nations (1982). *UN Convention on the Law of the Sea (UNCLOS), New York USA.*
United Nations (UN) (*1980). International Convention for the Safety of Life at Sea (SOLAS), New York USA.*
United Nations (UN) (*1982). UN Convention on the Law of the Sea (UNCLOS), New York USA.*
United Nations (UN) (2016) New Urban Agenda. Endorsed by the United Nations General Assembly at its Sixty-Eighth Plenary Meeting of the Seventy-First Session on 23 December 2016. ISBN: 97892-1-132731-1.
United Nations (UN) (2018). *Sustainable Development Goals.*
United Nations (UN) (2020) Global Issues: Big Data for Sustainable Development, United Nations, New York, NY.
United Nations (UN) (2023). *The Sustainable Development Goals Report: Special edition.* Towards a Rescue Plan for People and Planet.

United Nations Economic Commission for Europe (UNECE) (1996). Land Administration Guidelines with special reference to countries in transition. *Geneva, Switzerland*, 1996.
United Nations Integrated Geospatial Information Framework (UN IGIF) (2023). *A strategic guide to develop and strengthen national geospatial information management - Part 1: Overarching Strategy*. Second Edition 2023.
Van Osch, G.M., Lemmen, C.H.J. (2004) Appropriate Technologies for Good Land Administration Towards the Introduction of Workflow Management at the Netherlands Cadastre. *FIG Working Week 2004 Athens, Greece, May 22-27*, 2004.
Verhulst, S. (2021), Reusing data responsibly to achieve development goals. Development Co-operation Report 2021: Shaping a Just Digital Transformation, OECD Publishing, Paris.
Vranić, S., Matijević, H., Roić, M., Vučić, N. (2021) Extending LADM to support workflows and process models. *Land Use Policy*, 2021, 104, 105358.
Vučić, N., Vranić, S., Roić, M., Matijević, H. (2022), *Revision of Croatian LADM profile according to the new regulations in surveying profession*, 10th International FIG workshop on the Land Administration Domain Model, 31 March - 2 April 2022, Dubrovnik, Croatia.
W3C, OGC (2017) Semantic Sensor Network Ontology.
Webster, J.; Watson, R. (2002). Analysing the Past to Prepare for the Future: Writing a Literature Review. *Management Information Systems Quarterly*, 26(2).
Williamson, I. (1998). Using the case study methodology for cadastral reform. *Geomatica*, 52(3), 283-295.
Williamson, I. Enemark, S., Wallace, J., Rajabifard, A. (*2010). Land administration for sustainable development*. Citeseer.
World Bank (2013). *Land Governance Assessment Framework: Implementation Manual for Assessing Governance in the Land Sector*.
World Bank (2018). *Indicators, World Bank, Washington, DC*.
World Bank (2019). *Land Governance Assessment Framework*.
World Bank (2021). *World Development Report 2021: Data for Better Lives, World Bank, Washington, DC*.
World Bank (2024). *Land Governance Assessment Framework*.
Wu, D., Soon, K.H., Khoo, V. (2024). *Piloting 3D Cadastre in Singapore*. In Proceedings: 12th International FIG Land Administration Domain Model & 3D Land Administration Workshop. 24-26 September 2024, Kuching, Malaysia.
Xie, Y., Atazadeh, B., Rajabifard, A., Olfa, H. (2022). Automatic modelling of property ownership in BIM. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume X-4/W2-2022. *17th 3D GeoInfo Conference*, 19–21 October 2022, Sydney, Australia.
Xu, Z.; Zhuo, Y.; Li, G.; Bennett, RM; Liao, R.; Wu, C.; Wu, Y. (2022). An LADM–based model to facilitate land tenure reform of rural homesteads in China. *Land Use Policy*, 120:106271. doi: 10.1016/j.landusepol.2022.106271.
Ying, S., Guo, R., Li, L., van Oosterom, P.J.M., Ledoux, H., Stoter, S. (2011). *Design and Development of a 3D Cadastral System Prototype based on the LADM and 3D Topology*. In Proceedings: 2nd International Workshop on 3D Cadastres, November 2011, Delft, pp. 167-188.
Ying, S., Guo, R., Li, L., van Oosterom, P.J.M., Stoter, J. (2015). Construction of 3D volumetric objects for a 3D cadastral system. Trans. *GIS 19 (5)*, 758–779.
Zamzuri, A., Abdul Rahman, A., Hassan, M.I., van Oosterom, P.J.M. (2024). *Incorporating Legal Space Details of Building from BIM/IFC to the LADM Sarawak Country Profile*. In Proceedings: 12th International FIG Workshop on LADM & 3D LA. 24-26 September 2024, Kuching, Malaysia.
Zevenbergen, J.; de Jong, J. (2002), Public Law Information Regarding Land; Dutch proposal for registration, In FIG XXII International Congress, Washington D.C., USA.
Zulkifli, N.A., Abdul Rahman, A., Hassan, M.I., Choon, T. L. (2015). Conceptual Modelling of 3D Cadastre and LADM. *In Proceedings: World Cadastre Summit, Conference and Exhibition*, 2015, Istanbul, Turkey.
Zulkifli, N.A., Abdul Rahman, A., Jamil, H., Teng C.H., Tan L.C., Looi K.S., Chan K.L., van Oosterom, P.J.M. (2014). *Towards Malaysian LADM country profile for 2D and 3D Cadastral Registration System*. FIG Congress 2014 – Engaging the Challenges, Engaging the Relevance, Kuala Lumpur, Malaysia.
de Zeeuw, K. (2016). Land information data needs for SDG's, targets and indicators. *In 4th High Level Forum on United Nations Global Geospatial Information Management*, 20–22 April 2016, Addis Ababa, Ethiopia.

de Zeeuw, K., Benn, T., Unger, E.-M., & Bennett, R. B. (2020). The proposed United Nations framework for effective land administration (FELA): Progress, pathways and prospects. *In Proceedings of the Land and Poverty Conference, Washington, DC, USA*, 16–20 March 2020.

van Aalst, M. (2024) A standards-based portal for integrated Land Administration information. MSc thesis, Delft University of Technology.

van Capel, M.A., Chontos, C., Gheorghiu, A.I., Mbwanda, T. (2023). *Galileo High Accuracy Services - Analysis of its potential for cadastral surveying.* Student report, MSc Geomatics, TUDelft. Available online:.

van Oosterom P.J.M., (2013). *Research and development in 3D Cadastres, Computers, Environment and Urban Systems*, 40, pp. 1-6.

van Oosterom P.J.M., Stoter J., Ploeger H., van Oosterom P.J.M., Thompson R. and Karki S. (2014). *"Initial Analysis of the Second FIG 3D Cadastres Questionnaire: Status in 2014 and Expectations for 2018"*, 4th International Workshop on 3D Cadastres, Dubai, United Arab Emirates.

van Oosterom P.J.M., Stoter S., Ploeger H., Thompson R. and Karki S. (2011). *"World-wide Inventory of the Status of 3D Cadastres in 2010 and Expectations for 2014", FIG Working Week 2011, Marrakech, Morocco.*

van Oosterom P.J.M., Unger, E.M., Lemmen, C.H.J. (2022). *The second themed article collection on the land administration domain model (LADM), Land Use Policy*, 120.

van Oosterom, P.J.M., Dimopoulou, E. (2019). *Research and Development Progress in 3D Cadastral Systems; Printed Edition of the Special Issue Published in International Journal of Geo-Information; MDPI: Basel, Switzerland*, 2019; p. 302, ISBN1 978-3-03921-056-5, ISBN2 978-3-03921-057-2. Available online: https: //www.mdpi.com/books/pdfview/book/1753.

van Oosterom, P.J.M., Groothedde, A., Lemmen, C.H.J., van der Molen, P., Uitermark, H. (2009). Land Administration as a Cornerstone in the Global Spatial. International Journal of Spatial Data Infrastructures Research, Vol. *4*, 298-331.

van Oosterom, P.J.M., Lemmen, C.H.J. (*2015). Developing a second Edition of the Land Administration Domain Model - Trends in Spatial Domain Standards.* GIM International, December 2015. Available at:.

van Oosterom, P.J.M., Lemmen, C.H.J., Ingvarsson, T., van der Molen, P., Ploeger, H., Quak, C.W., Stoter, J.E., Zevenbergen, J.A. (2005). *The core cadastral domain model, in: Computers, Environment and Urban Systems*, 2005, Volume 30 (5), pp. 627-660.

van Oosterom, P.J.M., Paasch, J.M. (2023). *Proceedings of the 11th International Workshop on the Land Administration Domain Model and 3D Land Administration.* 11-13 October 2023, Gävle, Sweden.

Çağdaş, V., & Stubkjær, E. (2011). Design research for cadastral systems. *Computers, Environment and Urban Systems*, 35(1), 77–87. https://doi.org/10.1016/j.compenvurbsys.2010.07.003.

Çağdaş, V., Kara, A., van Oosterom, P. J. M., Lemmen, C. H. J., Işıkdağ, Ü., Kathmann, R., & Stubkjær, E. (2016). An initial design of ISO 19152:2012 LADM based valuation and taxation data model. *ISPRS Journal of Photogrammetry and Remote Sensing*, 4, 145–154.

Çetin, S., de Wolf, N., & Bocken, N. (2021). Circular digital built environment: An emerging framework. *Sustainability*, 13(11).

Østensen, O.M. (2018) Standards that make innovation possible – Digital Silk Road and International Partnerships. *Unites Nations World Geospatial Information Congress*, 20 November 2018, Dequing, Zhejiang Province, China (presentation).

ANNEX – Initial rubric assessment for 3D LASs

Based on the analysis of the questionnaire responses, Thompson et al. (2023) developed an initial assessment rubric to evaluate the progress of countries in implementing 3D LASs over the last 16 years. This rubric provides a scoring framework for nine Sections of the questionnaire, as outlined in section 2.3. The context of the rubric is presented in Table App. 1.1.

However, Sections 4, 11, 12, and 13 were excluded from the overall evaluation scoring. Section 4, which addresses X, Y coordinates, initially had a scoring method, but it was excluded after further assessment due to its limited utility. The final three Sections of the questionnaire include information that cannot be easily quantified for scoring purposes. For Section 11, which contains statistical data, no formal scoring was applied, but key factors such as the number of 2D and 3D spatial units, the population, and the total surface area of each country or jurisdiction were considered. These metrics, while not scored, provide valuable context for understanding the overall development of LASs in each country.

TABLE APP.1.1 Rubric assessment for the responses of the 4th FIG Questionnaire on 3D LA (Thompson et al., 2024)

Score	Description
SECTION 1 - GENERAL/ APPLICABLE 3D REAL-WORLD SITUATIONS	
0	3D spatial units are not recognised
2	3D spatial units recognised, but not as part of Cadastre/ LAS (with different legal system from 2D)
4	Legislation existing for 3D spatial units
6	Strata units and common property are recognised
8	Fully general 3D volumes are recognised as 'primary cadastral objects', representing the most frequently registered spatial units, with associated RRRs and linked persons.
10	Full LADM based support of 3D volumes.
SECTION 2 - INFRASTRUCTURE/ UTILITY NETWORKS	
0	Utility networks not recognised
2	Networks recognised but not as part of Cadastre/ LAS
4	Jurisdiction has privately owned/leased, etc. networks within Cadastre/ LAS
5	Networks recorded (within Cadastre/ LAS) in 2D
6	Networks are fully defined in 3D
8	Network sections are considered 'primary cadastral objects'
10	Full LADM based support of network objects
SECTION 3. - CONSTRUCTION/ BUILDING UNITS (including spatial extents of units defined in 3D by physical walls/objects)	
0	Units/apartments/construction units are not recognised
2	Units/apartments/construction units are recognised but not as parts of Cadastre/ LAS
4	Special legislation for 3D units, etc. exists
5	Meaning of boundaries is defined (middle of wall, etc.)
6	Full definition of buildings including common property
7[34]	Tenure is fully defined on units (protection against sale of 2D parcel)
8	Building units are considered 'primary cadastral objects'
9[35]	BIM is mandatory for registration of units in certain classes of buildings
10	BIM is mandatory for registration of all units
SECTION 5. - REPRESENTATION OF 3rd DIMENSION: HEIGHT (OR DEPTH)	
0	No ground surface model or definition of parcel height (2D) exists
2	2D parcels are defined in relation to local ground level, but not quantified
4	Jurisdictional height datum exists and is referenced
6	Ground surface elevation model exists but not is referenced by DCDB
7	Z-values are assigned on cadastral corners
8	Ground surface elevation model is carried within the DCDB (or is strongly connected)
10	Digital twin of the jurisdiction exists, including ground surface elevations

>>>

34 Note that the respective question was not included in the first edition of the Questionnaire - 2010
35 Note that the respective question was included first time in the 4th edition of the Questionnaire - 2022

TABLE APP.1.1 Rubric assessment for the responses of the 4th FIG Questionnaire on 3D LA (Thompson et al., 2024)

Score	Description
SECTION 6. - TEMPORAL ISSUES	
6a Real-world history	
4	Time-limited spatial units are defined, but actual limits are not being recorded within Cadastre/LAS
6	Time-limited spatial units exist and temporal limits are defined within Cadastre/LAS
8	Moving boundaries are defined in X/Y/Z/time
10	Full digital history of boundary changes is supported (including subdivisions)
6b Legality of title	
0	A full historic search of titles is needed going back to the first initial systematic registration
5	A limited historic search of dealings shall be carried out
10	The registry of titles is current, and the single current title is definitive
6c History of database	
0	The database(s) are point of time only (as up-to-date as possible)
2	Snapshots are taken at regular intervals
6	1D time – keeping reverse or forward deltas to track database changes
7	Some spatial units have 2 dimensions of time (database time and the real-world time)
8	Keeping a history of the database representation (The Versioned Object paradigm in LADM)[36]
10	Keeping real-world history as well as database representation history (The 2D time paradigm in LADM) [37]
SECTION 7. - RIGHTS, RESTRICTIONS AND RESPONSIBILITIES (RRRs)	
0	RRR information not available to Land Administration jurisdiction
4	Some distinctions in 3D RRRs compared to 2D
6	Same definition of 2D and 3D RRRs (and temporal if permitted) exist
10	RRRs are defined in form equivalent to LADM (or STDM)
SECTION 8. THE CADASTRAL DATABASE (Digital Cadastral Database - DCDB)	
0	No digital storage of Cadastral data exists
1	Graphics (in 2D) in a CAD / Graphics software, with the respective “attributes” stored in a textural database
2	The 2D graphics exist in a continuous (non-paged) storage scheme
4	The graphics and the attributes are stored within the same database & schema
5	Footprints of 3D parcels are stored in 2D, with an attribute indicating 3D
6	The 3D spatial units are stored in a separate repository
8	Link between the 3D and the 2D DCDBs (bi-directional link) exists
9	A single repository containing both 2D and 3D parcels with their full boundaries and attributes exists
10	A single repository, in LADM-compatible form, containing both 2D and 3D parcels with their full boundaries and attributes exists

>>>

36 The concept is explained in Thompson et al. (2021)
37 The concept is explained in Thompson et al. (2021)

TABLE APP.1.1 Rubric assessment for the responses of the 4th FIG Questionnaire on 3D LA (Thompson et al., 2024)

Score	Description
SECTION 9 - PLANS OF SURVEY (INCLUDING FIELD SKETCHES)	
9a Definition and format	
0	No plans of survey are registered
2	There is a registered plan of survey to define all 2D spatial units (one plan can define many spatial units)
4	There is a registered plan of survey to define all types of 2D and 3D spatial units
6	For a 3D spatial unit, the plan contains enough information to completely define the boundaries (for all types of spatial units, but this may involve a reference to the actual building walls)
8	There exist spatial units for which the definition of the boundaries is complete without reference to a building walls or other objects
10	LADM-compatible format of survey information able to define the boundaries definitively exists
9b Connection between survey plans and DCDB	
0	No connection – both are maintained separately
5	DCDB contains extracted data from the survey plans, but the survey plan information is final in defining cadastral boundaries.
7	There is an automatic process to extract data from survey plans into the DCDB, but DCDB is not definitive.
10	There is automatic cross data flow between survey plans and DCDB and information correctness in both is guaranteed.
SECTION 10 - DISSEMINATION OF 3D LAND ADMINISTRATION INFORMATION	
0	Cadastral maps are on paper form
1	Cadastral data available “in house” using network connections.
2	Spatial searches are allowed
3	Relevant software/hardware extend the availability of information dissemination
4	Multi-key access is provided (parcel identifier, house address, and other jurisdiction-specific keys)
5	Footprints of 3D parcels are depicted as 2D objects with colour or shading to indicate 3D or a 3D diagram is available through the 2D enquiry
6	The 3D spatial units are accessible to users with special software
7	3D spatial units are depicted on the 2D cadastral searches (the user doesn’t need to know if a spatial unit is 2D or 3D to search for it)
10	Both the 2D and 3D spatial units are depicted on the one query mechanism.

In Table App. 1.1., the rating scale ranges from 0 to 10, where 10 represents the most advanced and efficient status of a 3D LAS concerning the specific topic of the Section, and 0 represents the least developed or mature status within that concept. The scoring intervals across various Sections are not uniform, as they depend on the distinct details identifiable per topic that influence the scoring. For example, in Section 8 of the rubric, which pertains to the DCDB, multiple scoring options are provided, reflecting the significant variability in technical characteristics that impact the rating scale. In contrast, Section 7, which deals with RRRs, offers fewer scoring options, as the alternatives can be more readily grouped.

This assessment rubric represents a preliminary approach to quantify the questionnaire responses and track the progress of participating countries in implementing 3D LASs. Developed as part of the ongoing activities of the FIG Working Group on 3D Land Administration, the rubric offers a systematic approach to evaluation.

However, being a first-time development, several limitations must be acknowledged:

1. Questionnaire evolution: Changes to certain questions over time may impact consistency in responses across editions.
2. Participation variability: Not all respondents have participated in every edition of the questionnaire, and participation has been inconsistent across countries.
3. Interpretation challenges: Variations in responses may arise from differences in how respondents interpret the questions, which can be influenced by their familiarity with the questionnaire, the terminology used, and their level of expertise in LA.
4. Internal country variability: Even within the same country, interpretations of the questionnaire may differ across editions, as respondents are not always the same. Efforts were made in the latest edition to include both government organisations and academia to ensure diverse perspectives.
5. Analysis limitations: The analysis team's familiarity with certain countries enabled deeper insights, but unclear responses from some participants may have been subject to varying interpretations, potentially misaligning with the original intent.
6. Ranking complexity: Rankings are not always based on linear scoring, and overlaps or crossovers may occur in comparative analyses, but they are in an ordinal scale.

Using this rubric, rankings were calculated for eight countries—Greece, The Netherlands, South Korea, Turkey, China, Spain, Argentina, and Queensland. The diagrams provide a clear visualisation of each country's performance across the questionnaire Sections and their progress over the years. Apart from Queensland (Figure 2.14), the Netherlands (Figure 2.15) and Greece (Figure 2.16), the diagrams for the remaining five countries that have been examined, are presented in this Annex, (Figure App.1.1 till Figure App.1.5). These visualisations offer additional insights into the progress and trends observed in the 3D LAS implementation across these jurisdictions.

Figure App.1.1 illustrates the progress of South Korea's 3D LAS implementation across multiple categories from 2010 to 2022. The figure highlights a strong and steady performance in Section 3 (Building Units), demonstrating well-developed building-related cadastral data. However, significant gaps remain in Sections 4 (Coordinates) and 5 (Height), indicating areas requiring improvement. While Section 6b (Title Legality) previously showed lower scores, there has been notable progress in more recent years, reflecting advancements in legal frameworks for 3D cadastral registration. Additionally, improvements are visible in Sections 9a (Survey) and 9b (Connection), suggesting enhanced integration of survey data and connectivity within the system.

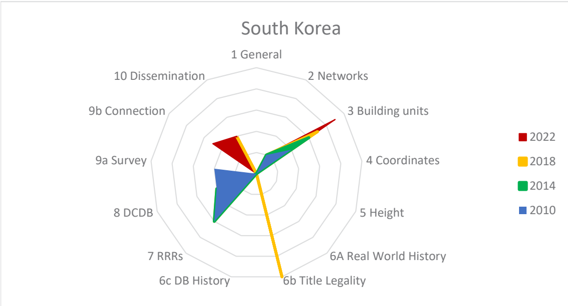

FIG. APP.1.1 South Korea's scoring in the various Sections of the questionnaires, over the years

Turkey's progress in 3D LAS implementation from 2010 to 2022 across various categories is illustrated in Figure App.1.2. Notably, there has been consistent strength in Section 3 (Building Units) and gradual improvements in Sections 9a (Survey) and 9b (Connection), reflecting enhanced integration of survey data and connectivity within the cadastral system. However, challenges remain in Sections 4 (Coordinates) and 5 (Height), indicating persistent gaps in the height support and representation. Section 6b (Title Legality) experienced significant fluctuations, showing lower scores in earlier years but demonstrating some improvements over time. The advancements in recent years, particularly in legal and administrative aspects, highlight Turkey's commitment to modernising its LAS.

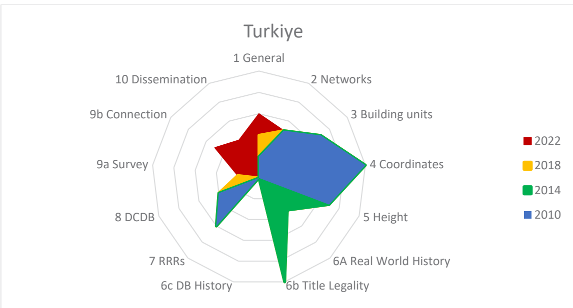

FIG. APP.1.2 Turkey's scoring in the various Sections of the questionnaires, over the years

Figure App.1.3 shows China's progress in 3D LAS implementation from 2010 to 2022, with strong performance observed in Sections 1 (General) and 10 (Dissemination), indicating a well-developed framework for information sharing and overall system governance. Improvements are also visible in Sections 3 (Building Units) and 4 (Coordinates), reflecting enhanced spatial data accuracy and integration efforts. However, Sections 6b (Title Legality) and 6c (Database History) show relatively lower scores, suggesting the need for further refinement in legal frameworks and historical data management. The chart highlights areas requiring attention, particularly in height representation (Section 5) and the dynamic connection of survey plans with cadastral databases (Sections 9a and 9b). China's steady development in multiple aspects of 3D LAS signals a structured approach to modernising its LAS while identifying key areas for future improvement.

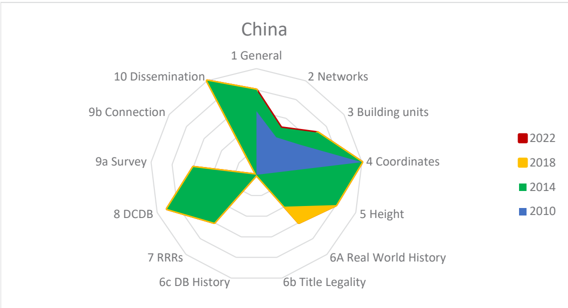

FIG. APP.1.3 China's scoring in the various Sections of the questionnaires, over the years

Spain's progress is presented in Figure App.1.4, highlighting developments and areas requiring further attention. Notable improvements are observed in Sections 9a (Survey) and 8 (DCDB), reflecting advancements in survey integration and cadastral database management. Strong performance is also evident in Sections 3 (Building Units) and 4 (Coordinates), indicating efforts to enhance spatial data representation. However, Sections 6b (Title Legality) and 6c (Database History) exhibit fluctuations, suggesting inconsistencies in legal frameworks and historical data tracking. Additionally, Section 5 (Height) remains underdeveloped, emphasising the need for further refinements in vertical accuracy within 3D LAS. While Spain has made notable strides, particularly in survey processes and cadastral database enhancements, challenges persist in fully integrating legal and historical data aspects, requiring continued improvements for a more comprehensive 3D LAS, according to country's answers in the questionnaire.

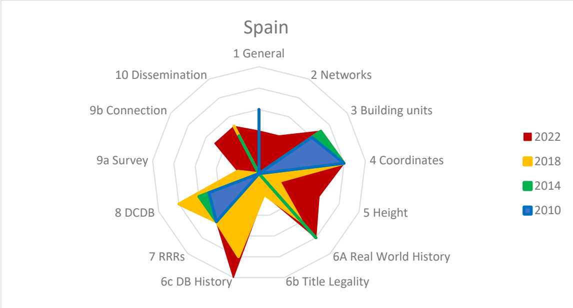

FIG. APP.1.4 Spain's scoring in the various Sections of the questionnaires, over the years

Finally, the diagram of Figure App.1.5, shows Argentina's progress in 3D LAS implementation, with notable advancements observed in Section 5 (Height), reflecting efforts to enhance vertical data representation, and in Section 3 (Building Units), indicating improvements in integrating building-related spatial data. Additionally, Sections 9a (Survey) and 8 (DCDB) exhibit strong performance, highlighting progress in survey methodologies and cadastral database management. However, inconsistencies are observed in Sections 6b (Title Legality) and 6c (Database History), suggesting gaps in legal and historical record integration. Moreover, limited improvements in Sections 1 (General) and 2 (Networks) point to ongoing challenges in establishing a fully interoperable and standardised 3D LAS framework.

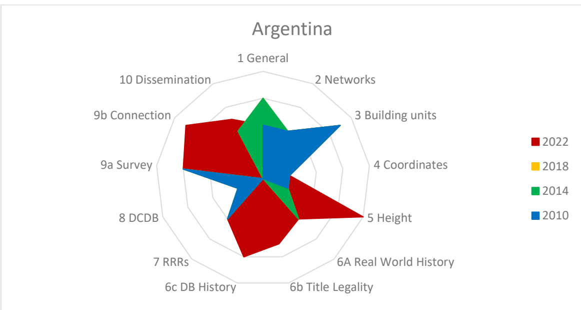

FIG. APP.1.5 Argentina's scoring in the various Sections of the questionnaires, over the years

Curriculum vitae

Eftychia Kalogianni (1989) was born in Ioannina, Greece. She received her MEng degree from the School of Rural, Surveying and Geoinformation Engineering of the National Technical University of Athens (Greece) in 2012 and an MSc in Geoinformatics from the same University in 2015. In 2016, she obtained her MSc in Geomatics from Delft University of Technology (The Netherlands), while spending some time in Technische Universität München for the course “Digital Methods for the Built Environment”.

After her studies, she started working as a surveyor and geoinformation engineer at a consulting engineering company in Greece, while continuing to be active in research collaborating with Prof Peter van Oosterom (TUDelft) and Prof Efi Dimopoulou (NTUA) and working as member of research teams at NTUA.

In 2018, Eftychia returned to TUDelft to join the GISt Section (currently Digital Technologies Section) at the Architectural Engineering and Technology Department, Faculty of Architecture and the Built Environment and continued her research as Ph.D. candidate under the supervision of Prof Peter van Oosterom, Prof Efi Dimopoulou (NTUA) and Prof Christiaan Lemmen (University of Twente). Her research has been funded and has contributed to the H2020 GISCAD-OV project related to the design, development and validation of an innovative and cost-effective Galileo High Accuracy Service for Cadastral Surveying applications, while she has been actively involved in the revision of the ISO 19152 LADM 19152. The research resulted in multiple papers in international journals and conferences.

During the course of her research work she has also been involved in teaching MSc and MEng courses (at TUDelft, NTUA and University of Piraeus), supervising MSc theses and an Honours Programme Master at TUDelft, as well as joining the Special Issue “*Broadening 3D Land Administration*” of Land Use Policy Journal as guest co-editor and the Photogrammetric Record as junior editorial board member, while assisted as a reviewer for leading international journals (LUP, Land, IJGI). She has participated in international collaborations, such as in ISO TC211 Geographic Information/ Geomatics WG7 Information Communities and CEN-CENELEC-ETSI Smart and Sustainable Cities and Communities Sector Forum (SF-SSCC)/ TG Local Digital Twins, as well as co-chair organising committees of international conferences, such as the joint event of the 7th International FIG Workshop on 3D Cadastres and the 16th 3D GeoInfo Conference 2021. She was co-author of the article that was awarded “FIG Article of the Month December 2019” regarding the advances in ISO1952 revision. Moreover, she has been working part time at a consulting engineering company in Greece (NAMA Consulting Engineers SA) and a geospatial software company in The Netherlands (Future Insight Group). At the moment, she is the Head of Office of the General Secretariat for Telecommunications and Post at the Hellenic Ministry of Digital Governance.

Currently, she is co-chair of the Joint Working Group 7.3 “*3D and LADM (3D/LADM)*” of FIG Commission 7 “Land Management and Cadastre” and FIG Commission 3 “Spatial Information Management” for the term 2023-2026, together with Prof Peter van Oosterom, Prof Alias Abhul Rahman and Dr Abdullah Kara.

Eftychia is married with Stathis and they have two sons, Sophocles and Stavros.

25#19

3D Land Administration in line with the Spatial Development Lifecycle

Eftychia Kalogianni

Land administration (LA) is a cornerstone of *sustainable development*, *environmental management*, and *inclusive governance*. Yet, many Land Administration Systems (LASs) remain fragmented and technologically outdated, limiting their capacity to meet rapid urbanisation, informal tenure, and increasing demands for transparent, data-driven decision-making.
Over the past decades, substantial research has been undertaken and prototypes developed for 3D LA solutions. The advantages of such approaches are well recognised: they provide greater legal certainty, enable more accurate property valuation, and establish a robust foundation for 3D spatial planning. Nevertheless, widespread implementation has not yet materialised, largely because the concept has been regarded as impractical at national scale. This dissertation investigates **how 3D LA can be integrated into the wider Spatial Development Lifecycle**, emphasising on *data reuse*, *interoperability* and *alignment with international standards*. It also investigates how legal, technical, and organisational dimensions of LA can converge with emerging technologies, including Building Information Model, crowdsourced surveys, and high-accuracy positioning.

The key contributions include:

- an **international standardised cadastral survey information model**;
- an **international standards' based cadastral survey workflow**;
- a **methodology for developing LADM-based country profiles**;
- an **international standardised 3D spatial profiles of varying complexity**;
- a **web-based 3D LA prototype**;
- the introduction of the **data lifecycle concept in 3D LA**.

Several of these concepts have been acknowledged by ISO and OGC and have already been adopted in LADM Edition II (ISO 19152-2:2025).
This work provides practitioners, policymakers, and researchers with the *tools* and *vision* to advance **innovative, transparent, and future-ready LASs**.

A+BE | Architecture and the Built Environment | TU Delft BK