LADM Colombia: A Model-Driven Ecosystem for Decision-Oriented Territorial Digital Twins toward LADM II

Golgi ALVAREZ, Colombia, David FRIEDRICH and Jörg WERTLI, Switzerland

Key words: Digital Twins, LADM II, Model-Driven Architecture (MDA), Land interoperability

SUMMARY

The technology industry is advancing irreversibly toward digital twins that integrate data, workflows, and services within unified territorial environments. Platform alliances and convergences clearly illustrate this trend: Autodesk + Esri connect BIM design with operational GIS; Hexagon integrates data capture, modeling, and geospatial/industrial analytics; Bentley Systems / Siemens orchestrate infrastructure life cycles through connected engineering. However, this technological convergence has also generated conceptual ambiguities, particularly between information systems, digital architectures, and digital twins in the strict sense, as well as between infrastructure-centered decisions and decisions of a territorial nature. Even so, this momentum is driving the dismantling of silos between cadastre, land registration, planning, infrastructure, and public services, enabling traceable decisions in (near) real time and frictionless interaction across domains.

Alongside technological supply, public-sector demand requires modernization based on shared rules. Standards thus become the balance between innovation and governance, and LADM stands as the most robust example in land administration. Its Version II expands the scope beyond the traditional cadastre–registration binomial, encompassing marine and coastal contexts, spatial planning, valuation, and infrastructure, through semantics and profiles that foster semantic and transactional interoperability across levels of government and sectors. This approach is essential to prioritize territorial decisions—related to rights, restrictions, and responsibilities—grounded in regulated territorial entities, which are not covered by infrastructure-only models but nonetheless require convergence with them at clearly defined points.

Within this context, Colombia is advancing a model-driven architecture (Model Driven Architecture, MDA) that, ahead of LADM II, organizes a conceptual core (LADM_COL) and thematic extended models for spatial planning, environment, mining, and other domains. This approach—supported by more than a decade of Swiss cooperation and the BSF-Swissphoto partnership—has resulted in a documented Land Administration System (LAS), published good practices, and a culture of interoperability, traceability, and citizen-oriented service; an appropriate foundation for evolving from information platforms toward decision-oriented territorial digital twins.

The challenge now is to balance standards and technological adoption with convergence in service of human, social, economic, and environmental development. This is not about "following the digital trend," nor about confusing digital twins with data repositories or software solutions, but about ensuring that LADM models, their extensions, and model-driven architectures enable better-informed, traceable public decisions, coherent with legal and administrative frameworks governing infrastructure, cities, and countries, while promoting transparency, territorial equity, and continuous improvement. In this sense, the need emerges for conceptual frameworks capable of positioning standards such as LADM II within broader ecosystems of domains, layers, and processes—where land administration goes beyond information management and becomes articulated with effective operation and decision-making in integrated digital environments.

RESUMEN

La industria tecnológica avanza de forma irreversible hacia gemelos digitales que integran datos, flujos de trabajo y servicios en entornos territoriales unificados. Las alianzas y convergencias de plataformas lo demuestran: Autodesk + Esri conectan diseño BIM con SIG operativo; Hexagon integra captura, modelado y analítica geoespacial/industrial; Bentley Systems / Siemens orquestan el ciclo de vida de infraestructuras con ingeniería conectada. Sin embargo, esta convergencia tecnológica también ha generado ambigüedades conceptuales, en particular entre sistemas de información, arquitecturas y gemelos digitales propiamente dichos, así como entre decisiones centradas en la infraestructura y decisiones de carácter territorial. Aun así, esta corriente empuja a superar silos entre catastro, registro, planeación, infraestructura y servicios públicos, habilitando decisiones trazables en tiempo (casi) real y sin fricción entre dominios.

Junto a la oferta tecnológica, la demanda pública requiere modernización con reglas comunes. Los estándares se convierten en el punto de equilibrio entre innovación y gobernanza, y el LADM es el ejemplo más sólido en administración del territorio. Su versión II amplía el foco más allá del binomio catastro–registro, abarcando contextos marino-costeros, planeación del suelo, avalúo e infraestructuras, con semánticas y perfiles que favorecen la interoperabilidad semántica y transaccional entre niveles de gobierno y sectores. Este enfoque resulta clave para priorizar decisiones territoriales —relacionadas con derechos, restricciones y responsabilidades— sustentadas en entidades territoriales reguladas, que no son cubiertas por modelos orientados exclusivamente a la infraestructura, pero que requieren convergencia con ellos en puntos bien definidos.

En este marco, Colombia impulsa una arquitectura orientada por modelos (*Model Driven Architecture, MDA*) que, adelantándose al LADM II, organiza un núcleo conceptual (LADM_COL) y modelos extendidos temáticos para ordenamiento territorial, ambiente, minería y otros dominios. Esta aproximación —sustentada por una década de cooperación suiza

y la alianza BSF-Swissphoto— derivó en un SAT documentado, buenas prácticas publicadas y una cultura de interoperabilidad, trazabilidad y servicio ciudadano; una base idónea para evolucionar desde plataformas de información hacia gemelos digitales territoriales orientados a la decisión.

El desafío ahora es equilibrar estándares y adopción tecnológica con una convergencia al servicio del desarrollo humano, social, económico y ambiental. No se trata de "seguir la moda" digital, ni de confundir gemelos digitales con repositorios de datos o soluciones de software, sino de asegurar que los modelos LADM, sus extensiones y las arquitecturas orientadas por modelos habiliten decisiones públicas mejor informadas, trazables y coherentes con marcos legales y administrativos sobre infraestructuras, ciudades y países, con transparencia, equidad territorial y mejora continua. En este sentido, se pone de relieve la necesidad de marcos conceptuales que permitan ubicar estándares como LADM II dentro de ecosistemas más amplios de dominios, capas y procesos, donde la administración del territorio no se limite a la gestión de información, sino que se articule con la operación efectiva y la toma de decisiones en entornos digitales integrados.

Colombia: A Model-Driven Ecosystem for Decision-Oriented Territorial Digital Twins toward LADM III

Golgi ALVAREZ, Colombia, David FRIEDRICH and Jörg WERTLI, Switzerland

INTRODUCTION

The concept of the digital twin has gained increasing prominence in public-sector digital transformation processes, particularly those related to territorial planning, management, and operation. Driven by the convergence of geospatial platforms, BIM, and advanced analytics solutions, multiple initiatives seek to integrate data, workflows, and services into unified digital environments that promise greater efficiency, transparency, and institutional responsiveness. Nevertheless, this rapid adoption has been accompanied by a heterogeneous use of the term digital twin, which in practice is applied indistinctly to data repositories, integrated information systems, or complex technological architectures, without a clear differentiation regarding their actual capacity to support decision-making.

This conceptual ambiguity is especially critical in the field of territorial management, where public decisions go beyond the mere digital representation of assets or infrastructure. While information systems and digital platforms play a fundamental role in organizing and visualizing data, a territorial digital twin, in the strict sense, should be understood as an active digital representation, linked to the real world, capable of reflecting states, relationships, and changes in the territory, and of incorporating rules, restrictions, and behaviors that enable scenario evaluation and support public decisions. The value of a digital twin therefore lies not in the software used or in the underlying technological architecture, but in its ability to improve the quality, timeliness, and traceability of decisions affecting citizens, institutions, and the territory as a whole, especially when such decisions are grounded in territorial entities with legal and administrative meaning.

In this context, it becomes necessary to distinguish between two types of decisions that are often conflated in digital twin initiatives. On the one hand, infrastructure-centered decisions focus on the design, construction, operation, and maintenance of specific physical assets, following technical life cycles and criteria typical of engineering and asset management. On the other hand, territorial decisions address what can be done, where, under what conditions, and with what legal, social, economic, and environmental implications, involving rights, restrictions, and responsibilities defined by public policies and regulatory frameworks. Although both dimensions are closely related, they respond to different logics and require complementary—but not interchangeable—conceptual models.

The convergence between geospatial technologies and BIM, widely promoted by the technology industry, has tended to prioritize infrastructure-centered approaches, supported by

robust models such as IFC. However, these models were not conceived to represent the legal and administrative complexity of the territory, nor to support decisions related to land governance, spatial planning, or rights management. In this sense, land administration requires a specific semantic framework capable of modeling regulated territorial entities, institutional actors, norms, and administrative processes, and of establishing clear points of convergence with infrastructure models when both domains interact.

International standards thus emerge as a key element for balancing technological innovation and public governance. ISO 19152 (LADM) has consolidated itself as the most solid reference for structuring information and processes associated with land administration (ISO, 2012). Its Version II significantly expands the scope of the model, moving beyond the traditional cadastre–registration focus to incorporate contexts such as spatial planning, marine and coastal environments, valuation, and the relationship with infrastructure, through a profile- and extension-based approach that fosters semantic and transactional interoperability across sectors and levels of government (ISO, 2024).

Building on this conceptual foundation, some countries have advanced toward model-driven approaches that anticipate the challenges of territorial digital twins. The case of Colombia is particularly relevant, having developed a Model Driven Architecture (MDA) that organizes a conceptual core based on LADM (LADM_COL) and a set of thematic extended models for domains such as spatial planning, environment, and mining. This approach, supported by more than a decade of international cooperation and institutional strengthening, has enabled the consolidation of a documented Land Administration System, with published good practices and a culture of interoperability, traceability, and citizen-oriented service.

This paper builds on that experience to analyze the role of LADM II as an enabler of decision-oriented territorial digital twins, from a perspective that prioritizes territory and public governance. The objective is not to propose a new technological platform or software solution, but to identify the conceptual, semantic, and architectural conditions required for digital twins to move beyond their technological dimension and become effective instruments for supporting public decisions—particularly those operating on territorial entities defined by legal and administrative frameworks. In this sense, the paper argues for the need for minimal and well-governed convergence frameworks between territorial and infrastructure models and explores how LADM profiles and extensions can help close gaps that currently limit the public value of many digital twin initiatives.

Finally, the paper is structured as follows: Section 1 examines the differences between digital files, information systems, and digital twins, as well as the distinction between territorial and infrastructure decisions; Section 2 presents a convergence approach based on standards and model-driven architectures; Section 3 analyzes the Colombian case as a model-driven ecosystem oriented toward LADM II; Section 4 discusses the expansion beyond the cadastre–registration domain through extended models and thematic convergence; Section 5 examines

the LADM_COL-POT profile as an example of articulation between spatial planning and other domains; and Section 6 proposes elements to evaluate and guide the adoption of territorial digital twins from a governance and public-value perspective.

1. FROM DIGITAL FILES TO TERRITORIAL DIGITAL TWINS

1.1. Clarifying concepts: information, architecture, and decision

The rapid adoption of the digital twin concept in the field of territorial management has been accompanied by a wide diversity of interpretations. In many cases, initiatives that integrate geospatial data, BIM models, or analytical platforms are presented as digital twins, even when their functionality is limited to visualization, consultation, or information integration. This situation not only generates conceptual confusion but also makes it difficult to assess the real value that such initiatives contribute to public decision-making.

To clarify this landscape, it is necessary to distinguish between three conceptual levels that, although related, are not equivalent: the digital file, the information system or architecture, and the digital twin proper.

A digital file primarily fulfills a storage function. It may be structured, standardized, and even updated at high frequency, but its main purpose is to preserve information and facilitate access to it. Cadastral databases, repositories of geographic layers, or libraries of BIM models fall within this level. Their value lies in institutional memory and data availability, but they do not incorporate analytical capabilities or feedback mechanisms toward public action.

An information system or digital architecture integrates multiple files and data sources, typically through platforms that enable technical interoperability, advanced visualization, and descriptive analysis. At this level there are many corporate GIS systems, service-oriented architectures, or integrated urban platforms. These systems improve institutional management and coordination, but their scope is usually limited to answering questions such as “what exists” or “what has happened,” without explicitly incorporating rules, behaviors, or evaluations of future scenarios.

A territorial digital twin, by contrast, should be understood as an active digital representation of the territory, closely linked to its physical, legal, and administrative counterpart. Its objective is not merely to represent information, but to support decisions. To do so, it must be capable of reflecting states and changes over time, incorporating rules and restrictions derived from public policies, and enabling the evaluation of alternative scenarios and their potential impacts. From this perspective, the digital twin is not a technological product or a specific platform, but an emergent capability resulting from the coherent integration of data, models, processes, and

governance—especially when such integration is organized around territorial entities that produce legal and administrative effects.

This distinction is particularly relevant in the public sector, where territorial decisions have long-term legal, social, and environmental implications. Confusing an information system with a digital twin can lead to technological investments that do not translate into better decisions or greater public value, generating institutional frustration and misalignment between expectations and outcomes.

1.2. Territorial decisions and infrastructure decisions

The need to clarify the concept of the digital twin is directly related to another fundamental distinction: the difference between territorial decisions and infrastructure-centered decisions. Although both interact constantly, they respond to different natures and require complementary—but not interchangeable—conceptual models.

Infrastructure decisions focus on the design, construction, operation, and maintenance of specific physical assets. These decisions unfold within well-defined technical life cycles and are guided by criteria of performance, cost, safety, and operational efficiency. In this domain, BIM models and the IFC standard provide a solid basis for representing constructive components, technical relationships, and physical properties, facilitating interdisciplinary coordination and asset life-cycle management.

Territorial decisions, on the other hand, address broader and more transversal issues: which uses are permitted in a given space, under what regulatory conditions, with what effects on existing rights, and how public and private interests are balanced within the territory. These decisions do not operate solely on space as a physical fact, but on spatial entities defined by legal and administrative frameworks, involving rights, restrictions, and responsibilities that condition public action. They involve multiple institutional actors, operate across different administrative and temporal scales, and are deeply linked to public policies and governance processes.

The growing convergence between geospatial technologies and BIM has tended to prioritize infrastructure-centered approaches, driven by the maturity of tools and models available in that domain. However, directly transferring this logic to the territorial domain entails the risk of obscuring key dimensions of public decision-making that are not covered by engineering-oriented models. By design, IFC does not natively incorporate the representation of property rights, complex regulatory restrictions, or administrative responsibilities—not because these aspects are irrelevant, but because they exceed their conceptual scope.

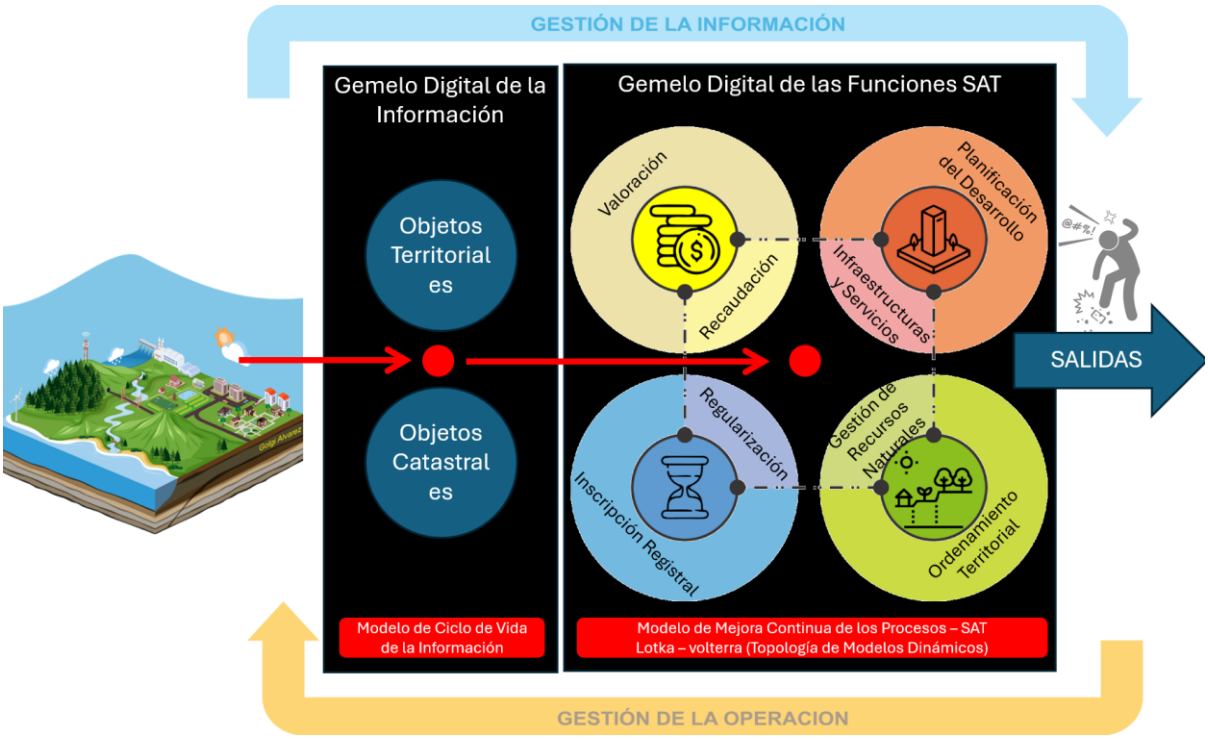
1.3. The need for convergence: complementarity without substitution

Recognizing these differences does not imply establishing a dichotomy between territorial models and infrastructure models. On the contrary, many public decisions require interaction between both domains: infrastructure is implemented on regulated territory; projects must respect existing rights and land-use restrictions; and territorial planning conditions the technical and economic feasibility of infrastructure projects.

The central issue, therefore, is not choosing between LADM or IFC, but establishing minimal and well-governed convergence mechanisms that enable interoperability between models without losing semantic integrity. Such convergence should occur at clearly defined points, such as shared spatial identification, references to administrative or legal units, and the traceability of decisions that affect both the territory and built assets.

From a territorial governance perspective, it is essential to prioritize models that adequately represent public decisions, the regulatory frameworks that underpin them, and their evolution over time. In this regard, LADM provides the semantic foundation necessary to model the territory as a system of rights, restrictions, and responsibilities, explicitly incorporating historical versioning of information and the traceability of normative and administrative changes. This approach establishes a solid anchoring point for subsequent convergence with infrastructure models when decisions require it, without losing legal coherence or temporal continuity (Figure 1).

Figure 1 Land Administration Digital Twin approach integrating information, LAS functions, and operational decisions



Source: SwissTierras Colombia Project

This prioritization does not diminish the importance of BIM or IFC models but rather places each standard in the role for which it was conceived. A territorial-first approach ensures that public-sector digital twins do not become mere technological extensions of asset management but instead consolidate as instruments in the service of informed, transparent decisions aligned with public policies.

1.4. Implications for territorial digital twins

Considering these distinctions, territorial digital twins should be conceived as decision-oriented systems, where technological integration is a means rather than an end. Their effectiveness depends on the existence of clear conceptual models, shared standards, and governance mechanisms that allow information, processes, and actors to be articulated coherently—particularly when decisions are structured around territorial objects with legal and administrative significance.

Within this framework, LADM II emerges as a key enabler for structuring the territorial dimension of digital twins, by providing a common language to represent legal spaces, institutional actors, and rules that condition land use and transformation. Convergence with infrastructure models, when required, must be built on this foundation, ensuring that territorial decisions retain their centrality and that the benefits of digital transformation translate into tangible public value.

2. A CONVERGENCE APPROACH BASED ON STANDARDS AND MODEL-DRIVEN ARCHITECTURES

2.1. The legal territorial object as the semantic unit of decision

One of the fundamental conceptual contributions for understanding the role of territorial digital twins is the distinction between territory as a physical fact and territory as a legal–institutional construct. In many territorial information systems, this difference is not made explicit, leading to geographic data and public decisions being treated within the same semantic plane. From a land administration perspective, however, this distinction is essential.

A geographic datum describes an observable fact of the real world. It may represent a natural or built element—such as a river, a building, a road, or a slope—and exists independently of any regulatory framework. Its value lies in describing physical reality and supporting technical, environmental, or engineering analyses. This type of information constitutes the traditional foundation of geospatial systems.

A legal territorial object, by contrast, does not exist solely because of its physical manifestation, but because it has been defined, recognized, or regulated by a legal or administrative framework. It is a spatial entity that produces legal and administrative effects through its association with rights, restrictions, and responsibilities (RRR). Cadastral parcels, environmental determinations, land-use zones, protected areas, easements, or impact zones are examples of legal territorial objects. Although all of them rely on geometry, their meaning does not reside in form, but in the consequences, they generate for public decision-making.

This approach originates in the philosophical conception of cadastre promoted by Cadastre 2014 and its evolution toward Cadastre 2014–2034, where cadastre ceases to be understood as an inventory of parcels and becomes a system of information about legal relations to land. The ISO 19152 standard (LADM) formalizes this vision by explicitly modeling the relationships between actors (parties), rights, restrictions, and responsibilities, administrative units, and spatial units. In this sense, LADM does not model territory as a set of isolated geographic objects, but as a system of legally expressed spatial relationships.

The concept of the legal territorial object thus constitutes the basic semantic unit for decision-oriented territorial digital twins. Unlike approaches focused exclusively on data or geometries,

it allows territorial information to be structured according to its legal, administrative, and decisional relevance, laying the foundations for coherent digital governance.

2.2. Territorial decisions and infrastructure decisions: differentiated scopes

The centrality of the legal territorial object helps clarify another key distinction in the digital twin debate: the difference between territorial decisions and infrastructure decisions. Although they interact continuously, they respond to different natures and require complementary—but not interchangeable—conceptual models.

Infrastructure decisions focus on the design, construction, operation, and maintenance of specific physical assets. Their emphasis lies on technical performance, safety, costs, and operational efficiency throughout the asset life cycle. These decisions rely on detailed models of constructive components and technical relationships, where BIM standards—and particularly IFC—provide a robust and widely adopted representation.

Territorial decisions, in contrast, focus on defining what can be done in each space, under which regulatory conditions, with what implications for existing rights, and with what social, economic, and environmental impacts. These decisions do not concern an isolated asset, but the territory as a regulated system, mediated by public policies, legal frameworks, and institutions. In this domain, legal territorial objects constitute the primary reference, as they are the entities through which public decisions materialized in space.

The growing convergence between geospatial technologies and BIM has tended to privilege infrastructure-driven approaches, extrapolating models designed for assets to broader territorial problems. However, infrastructure-oriented models do not natively incorporate the representation of property rights, complex regulatory restrictions, or administrative responsibilities—not due to technical limitations, but because these elements lie beyond their conceptual scope. This difference highlights the need for specific territorial models capable of structuring the context within which infrastructures are planned, authorized, and managed.

2.3. Convergence at minimums: interoperability without semantic loss

Recognizing the difference between territorial and infrastructure decisions does not imply separating them into independent silos. On the contrary, many public decisions require interaction between both domains: infrastructure is implemented within regulated territory; projects must respect existing rights and land-use restrictions; and territorial planning conditions the technical, legal, and economic feasibility of infrastructure projects.

The central issue, therefore, is not substituting one model for another, but defining minimal and well-governed convergence mechanisms that enable interoperability between domains without losing semantic integrity. Such convergence should occur at clearly defined points that are

sufficient for decision-making, such as shared spatial identification, references to legal territorial objects, and the traceability of decisions affecting both territory and built assets.

From this perspective, convergence does not consist of merging geospatial and BIM models into a single structure, but of establishing explicit and delimited relationships between them, while respecting the role of each standard. In many cases, this interaction can take place through well-defined minimums: from the infrastructure side, a road or corridor centerline; from the territorial side, an area of influence or buffer around that axis, within which regulations, restrictions, and administrative decisions apply. Although each domain may manage much richer levels of detail and specialization, the interaction is concentrated at these essential points of contact.

LADM provides the semantic framework that defines the "where" and the "under what conditions" of territorial decisions, while infrastructure models describe "how" those decisions are technically materialized. This relationship is not unidirectional: the construction of infrastructure can generate new information relevant to land administration—such as affected spaces, easements, or constructed units with legal implications—which feeds processes such as valuation updates, regulatory enforcement, or the review of territorial restrictions. In this way, complementarity between both domains remains manageable, traceable, and decision-oriented, constituting an operational foundation for decision-oriented territorial digital twins.

2.4. Model-driven architectures as support for convergence

Model Driven Architectures (MDA) constitute a key mechanism for operationalizing this convergence. By prioritizing the definition of conceptual and logical models independent of technology, MDA allows legal territorial objects, their relationships, and associated rules to remain stable, even as platforms and technical solutions evolve. In this sense, Alvarez and Wertli (2019) highlight the role of MDA in ensuring semantic consistency and long-term interoperability across institutional and technological changes.

Within an MDA approach, legal territorial objects are defined at the conceptual level, formalized through interoperable logical models and profiles, and implemented via services, databases, and applications at the physical level. This separation facilitates scalability, reuse, and the gradual adoption of standards, reducing technological dependencies and strengthening territorial information governance.

For territorial digital twins, this approach is particularly relevant, as it enables the incorporation of new thematic domains—such as planning, environment, or infrastructure—without compromising the coherence of the territorial core. In this way, convergence between geospatial

technologies and BIM is built on a solid semantic foundation centered on legal territorial objects and the public decisions they enable.

2.5. Implications for decision-oriented digital twins

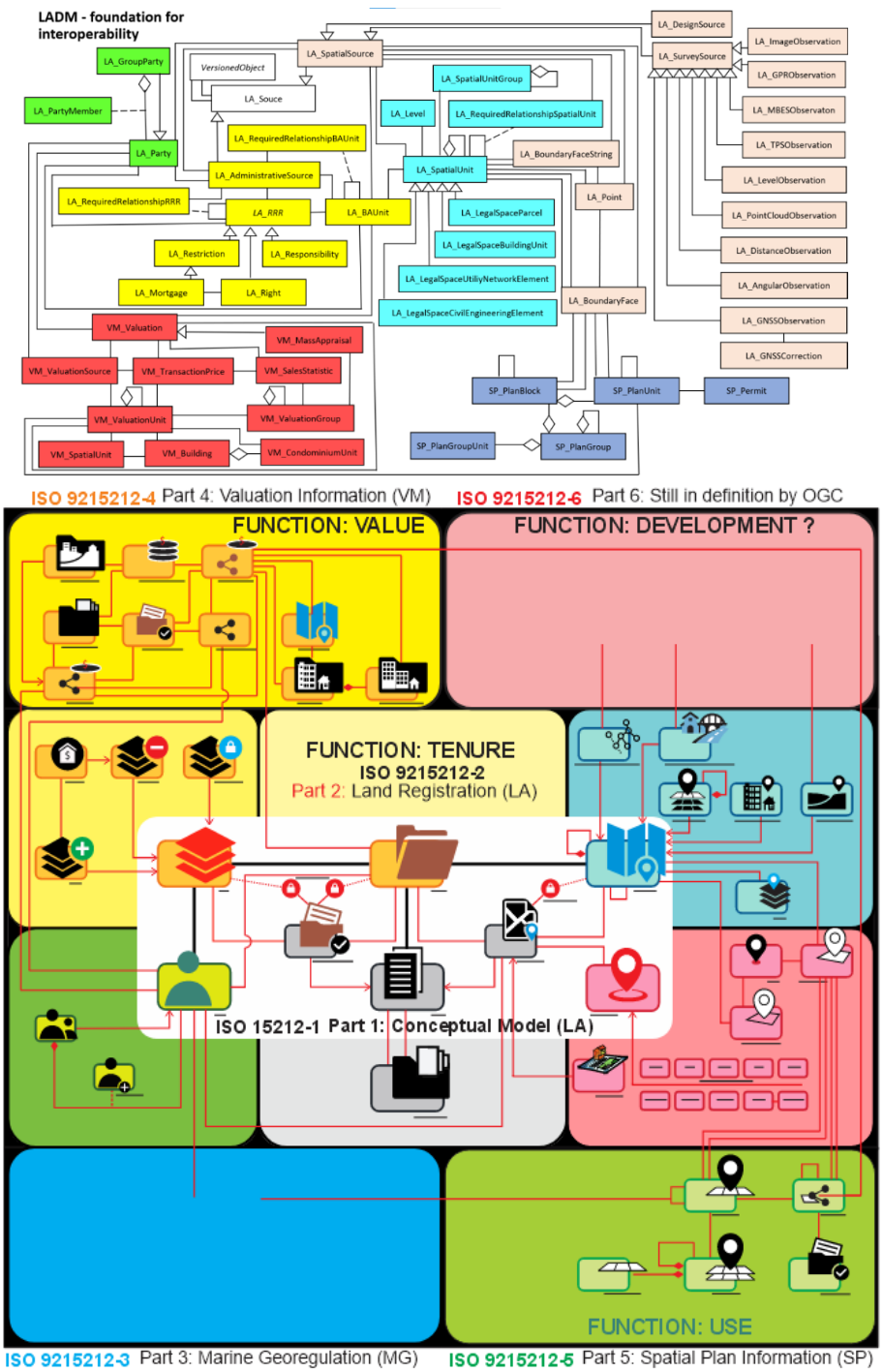
Based on the foregoing, territorial digital twins should be conceived as decision-oriented systems, where technological integration is a means rather than an end. Their effectiveness depends on the ability to represent legal territorial objects, articulate them with geographic data and infrastructure models, and link them to administrative processes and explicit rules.

Within this framework, LADM II emerges as a structural enabler for the development of territorial digital twins, not only by extending the scope of land administration beyond the traditional cadastre–land registration domain, but also by rationalizing the organization of territorial information models. Rather than encouraging an open-ended proliferation of thematic models, LADM II groups domains with similar behavioral and decisional characteristics into a limited set of coherent parts, closely aligned with the well-established land administration functions of tenure, use, value, and development.

In this modular structure, ISO 19152-1 provides a shared conceptual foundation across all domains; ISO 19152-2 (Land Registration, LA) primarily addresses tenure-related functions; ISO 19152-4 (Valuation Information, VM) focuses on value; ISO 19152-5 (Spatial Plan Information, SP) aligns with land use and planning; and ISO 19152-3 (Marine Georegulation, MG) extends these principles to the marine and coastal context. A sixth part, ISO 19152-6, currently under development within OGC, is expected to complement this structure by addressing aspects associated with territorial development (Figure 2).

This organization helps control semantic entropy by concentrating related behaviors, rules, and decision contexts within a small number of well-defined domains, while preserving interoperability through a common conceptual core. For decision-oriented territorial digital twins, this approach provides a scalable and governable foundation, enabling convergence with infrastructure models where needed, without diluting the central role of territorial decisions or compromising legal and institutional coherence.

Figure 1 LADM II conceptual model and its functional interpretation for land administration



Source top: FIG; Source bottom: Author interpretation aligning LADM II Parts with land administration functions

3. COLOMBIA AS A MODEL-DRIVEN ECOSYSTEM TOWARD LADM II

3.1. From sectoral implementation to an integrated territorial ecosystem

Colombia's experience in land administration constitutes a relevant reference for analyzing how the conceptual principles discussed in previous sections can be materialized within a real institutional environment. Unlike approaches centered on individual projects or isolated systems, the Colombian approach has evolved toward the progressive construction of a model-driven territorial ecosystem, in which standards, interoperability, and information governance are conceived as strategic assets of the State.

This process did not emerge as a direct response to the recent notion of digital twins, but rather as the result of a structural need to modernize land administration in a context characterized by high institutional complexity, regulatory diversity, and multiple decision scales. In this sense, the early adoption of LADM and the development of derived models preceded the popularization of the term "digital twin," allowing the Colombian case to be analyzed from a perspective less influenced by technological trends and more focused on solving concrete public problems.

3.2. LADM_COL as the conceptual core of the Land Administration System

At the center of the Colombian approach lies the definition of a common conceptual core, known as LADM_COL, aligned with ISO 19152 and adapted to the country's legal and institutional context. This core is not conceived as a closed model, but as a stable semantic foundation upon which multiple thematic domains related to land administration are articulated (CONPES, 2020).

LADM_COL explicitly structures the fundamental elements of territory from a legal–administrative perspective, modeling actors, rights, restrictions, and responsibilities, as well as the spatial units over which they are exercised. In this way, territory is represented not merely as a geographic surface, but as a system of legally expressed spatial relationships, consistent with the philosophy of Cadastre 2014–2034 and with the principles underpinning the evolution toward LADM II (FIG, 2014).

This conceptual core plays a key role in terms of interoperability: it enables different sectors and levels of government to share a common understanding of legal territorial objects, even when each manages specific information and operates under particular regulatory frameworks.

Rather than forcing the homogenization of systems or processes, LADM_COL acts as a common language that facilitates the integration and traceability of territorial decisions.

3.3. Thematic extended models and progressive specialization

Building on LADM_COL, Colombia has developed a set of thematic extended models that respond to the specific needs of different public policy domains, such as spatial planning, environment, mining, and other sectors with direct influence on land use and management. These models do not replace the core; instead, they specialize in maintaining semantic coherence and structural compatibility.

This strategy of progressive specialization makes it possible to address territorial complexity without resorting to monolithic models. Each domain can define its own legal territorial objects, rules, and processes, as long as alignment with the common conceptual core is preserved. In practical terms, this translates into greater capacity to integrate information, assess cross-sector impacts, and coordinate decisions among sectors that have traditionally operated in a fragmented manner.

From the perspective of territorial digital twins, this approach is particularly relevant, as it enables the gradual incorporation of new layers of analysis and simulation without compromising system coherence. Digital twins are not built as isolated solutions, but as emerging capabilities supported by an ecosystem of interoperable models.

3.4. Model-driven architecture and governance of interoperability

The development of LADM_COL and its extended models has been supported by a Model Driven Architecture (MDA), which clearly separates the conceptual, logical, and physical levels. This separation has allowed normative, institutional, and technological evolution to be managed in a controlled manner, avoiding excessive dependence on specific platforms and facilitating adaptation to new standards such as LADM II.

Within this approach, conceptual models define the meaning and relationships of legal territorial objects; logical models formalize these definitions into interoperable schemas; and physical implementations materialize the models in concrete systems, services, and applications. This structure not only favors scalability and ecosystem sustainability but also strengthens the governance of interoperability by making design decisions and their implications explicit.

This approach has been documented through a series of national and territorial good practices developed under the SwissTierras program, which describe the application of model-driven

architecture, interoperability principles, and governance arrangements in real institutional settings (SwissTierras, s.f.).

The Colombian experience demonstrates that effective interoperability is not achieved solely by connecting systems, but through the governance of the models that underpin those systems. This perspective is consistent with the vision of territorial digital twins as decision-oriented instruments, where traceability, transparency, and institutional accountability are as important as technological integration.

3.5. An ecosystem anticipating the challenges of LADM II and digital twins

From this perspective, the Colombian ecosystem can be understood as an environment that anticipates many of the challenges posed by LADM II and the adoption of territorial digital twins. The expansion of scope toward domains such as spatial planning, marine-coastal environments, valuation, and the relationship with infrastructure is already being addressed through extended models and well-defined convergence mechanisms.

Rather than constituting a literal implementation of LADM II, the Colombian case provides evidence of how a model-driven approach can prepare institutions to incorporate new standards and digital capabilities without structural disruption. In this sense, the transition toward territorial digital twins does not represent an abrupt change, but rather a natural evolution of a system that already prioritizes territorial decisions based on legal territorial objects, semantic interoperability, and information governance.

This experience offers a valuable reference framework for other countries and organizations seeking to advance toward decision-oriented territorial digital twins focused on public value, demonstrating that the key lies not in adopting specific technologies, but in building conceptually solid, model-driven, and decision-oriented ecosystems.

4. BEYOND CADASTRE–LAND REGISTRATION: TERRITORIAL DOMAINS, EXTENDED MODELS, AND THEMATIC CONVERGENCE

4.1. From the cadastre–land registration binomial to the first extended model

Historically, land administration has been dominated by the cadastre–land registration binomial, primarily focused on parcel identification and the formalization of property rights. While this approach has been fundamental for ensuring legal certainty and institutional stability,

it is insufficient to address the complexity of contemporary territorial decisions, which go beyond ownership to encompass environmental, social, economic, and planning dimensions.

According to Alvarez and Gil (2023), the Colombian experience reflects a shift from a cadastre-centric approach toward a comprehensive land administration paradigm. Within this framework, the cadastre–land registration binomial was not defined as the system's core, but as the first extended model built upon a shared conceptual foundation. From the outset of the modernization process, cadastre and land registration were understood as addressing a specific land administration domain—tenure and real rights—and were therefore modeled as a coherent specialization rather than as a representation of the entire system.

This approach enabled land administration to evolve from a logic exclusively centered on property toward a broader vision in which territory is understood as a dynamic system of legal territorial objects associated with multiple rights, restrictions, and responsibilities. This

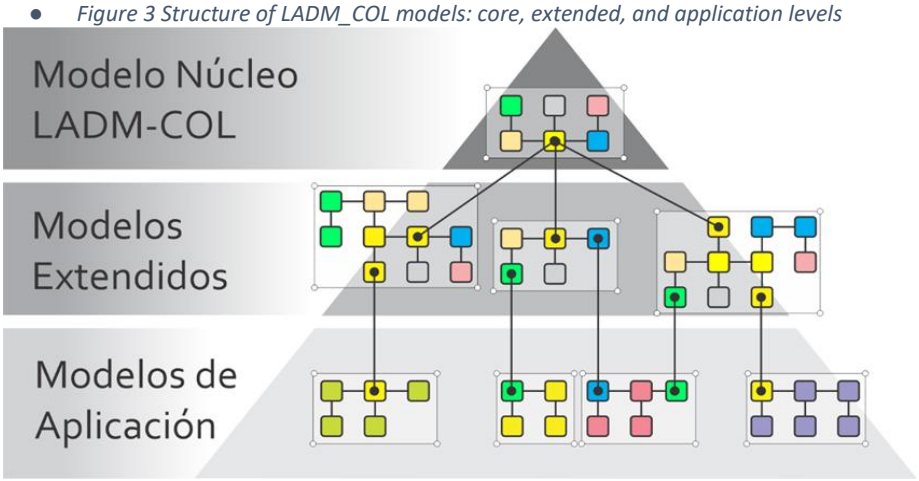
conceptual evolution, initiated prior to the formal publication of LADM II, anticipated the paradigm shift that would later be consolidated in the new version of the standard.

4.2. Three levels of models: core, extended, and application

One of the distinctive features of the Colombian approach is the explicit definition of three levels of models (Figure 3) aligned with a model-driven architecture:

- Core model, represented by LADM_COL, which defines the fundamental concepts of land administration from a legal–administrative perspective, including actors, rights, restrictions, responsibilities, and spatial units.
- Extended models, which specialize the core for specific thematic domains, such as cadastre–land registration, spatial planning, environment, mining, and other sectors with spatial relevance.
- Application models, which translate the extended models into concrete operational schemas for information systems, services, and specific institutional processes.

Figure 3 Structure of LADM_COL models: core, extended, and application levels



Source: SwissTierras Colombia Project

This separation makes it possible to manage territorial complexity without resorting to monolithic models. The core provides semantic stability; extended models enable regulatory

and sectoral adaptation; and application models support technological implementation while respecting the institutional and operational specificities of each entity.

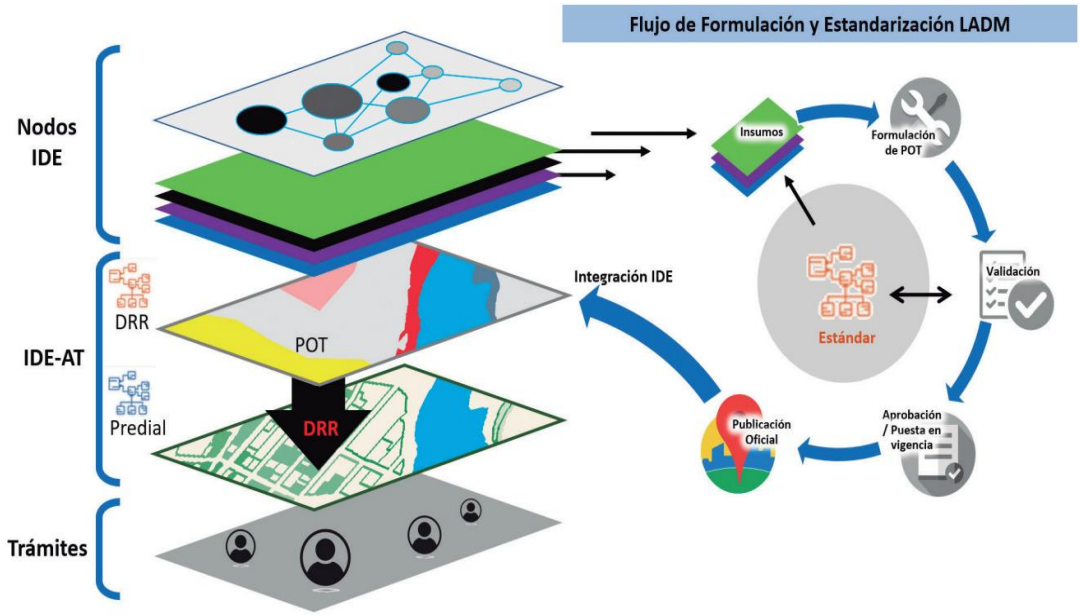
From the perspective of territorial digital twins, this stratification is particularly relevant, as it allows digital capabilities to evolve progressively, maintaining conceptual coherence and avoiding rigid dependencies between public policy, information models, and technology.

4.3. Legal territorial objects as a common element across domains

The effective integration of domains such as cadastre–land registration, spatial planning, environment, valuation, or infrastructure requires a common semantic element that allows information, rules, and processes to be articulated without diluting sector-specific characteristics. In the Colombian approach, this role is fulfilled by *legal territorial objects*, understood as spatial entities defined primarily by their legal and administrative effects rather than solely by their geometry.

Under this perspective, legal territorial objects emerging in different domains—such as a parcel in the cadastre–land registration model or a protected area in the environmental domain—share the same fundamental conceptual structure. From the LADM viewpoint, both are modeled as entities with parties, authoritative sources, spatial representation, and associated rights, restrictions, and responsibilities. The distinction between them lies not in the model structure itself, but in their specific attributes and, most importantly, in the business rules that govern their interaction with other legal territorial objects (Figure 4).

Figure 4 LADM - RRR schema model



Source: SwissTierras Colombia Project

The development and implementation of extended models such as LADM_COL-POT are documented in detail in the SwissTierras national and territorial good practices, which describe how these semantic models are translated into operational applications and public services (SwissTierras, s.f.).

Thus, while in the cadastre–land registration model these objects typically manifest as parcels associated with real rights, in spatial planning they are expressed as regulatory units, and in the environmental domain as protected areas or management units. In all cases, geometry constitutes necessary support, but decisional meaning emerges from the regulatory framework and from the rules that determine which rights, restrictions, and responsibilities apply when these objects interact with one another. From this perspective, it is not the isolated object that defines RRRs, but rather the relationships and intersections between models, for example, between a parcel and a protected area—that enable coherent and traceable territorial decisions.

This conception makes it possible to clearly distinguish between descriptive geographic data and entities that structure public decision-making, establishing a common foundation for thematic convergence without imposing artificial uniformity across domains.

4.4. Extended models and LADM profiles as an anticipatory strategy

The extended models developed in Colombia emerged in response to concrete institutional needs and predate the publication of LADM II. Their design was based on principles of semantic coherence and reuse of the conceptual core, aligned with a model-driven architecture,

even when the notion of profiles and extensions had not yet been formally consolidated within the international standard.

With the publication of LADM II, this strategy was validated and reinforced by explicitly establishing profiles as the mechanism for adapting the model to different contexts and domains. In this sense, the Colombian extended models can be understood as natural precursors to the LADM II profile logic, demonstrating that a model-driven approach makes it possible to anticipate normative evolution without generating conceptual ruptures.

This continuity is particularly relevant for the development of territorial digital twins, as it ensures that new analytical and simulation capabilities can be incorporated on a stable and governable semantic foundation.

4.5. Convergence with infrastructure: clear and governed interfaces

Expanding land administration beyond the cadastre–land registration domain does not imply diminishing the role of infrastructure in territorial development. Many strategic decisions lie at the intersection of spatial planning and infrastructure projects, where land-use regulations, existing rights, environmental restrictions, and technical considerations converge.

In this context, convergence between territorial models and infrastructure models should be addressed through clear and well-governed interfaces, rather than through the substitution of one set of models by another. LADM-based extended models define the territorial and regulatory context within which an infrastructure can be planned and authorized, while BIM and IFC models describe how that infrastructure is technically materialized.

For territorial digital twins, this interface-based convergence allows infrastructure information to be integrated insofar as it interacts with legal territorial objects, while always preserving the primacy of territorial decisions and the normative frameworks that underpin them.

4.6. Implications for planning and public decision-making

The explicit definition of a core model, extended models, and application models creates favorable conditions for more integrated spatial planning and better-informed public decision-making. Within this framework, territorial digital twins can operate as analysis and simulation environments that integrate physical data, legal rules, and public policy scenarios.

By structuring these capabilities around legal territorial objects and interoperable models, decision traceability, cross-domain impact assessment, and institutional accountability are strengthened. The Colombian experience demonstrates that advancing toward territorial digital

twins does not depend on the adoption of specific technologies, but on the progressive construction of a conceptually solid, anticipatory, and public-value-oriented model ecosystem.

5. LADM_COL-POT: SPATIAL PLANNING AS A DECISION-ORIENTED PROFILE

5.1. Spatial planning as a priority decision-making domain

Spatial planning is one of the areas where the limitations of the traditional cadastre–land registration approach become most evident, and where the need for extended models becomes most critical. Decisions related to territorial planning do not refer solely to parcel delimitation or the formalization of rights, but to the definition of permitted uses, regulatory conditions, environmental restrictions, and development guidelines that affect multiple actors and administrative scales.

In this context, spatial planning operates fundamentally on legal territorial objects, such as land-use zones, regulatory areas, planning instruments, and management units, which produce direct legal effects on the territory. Proper modeling of these objects is essential to ensure regulatory coherence, decision traceability, and articulation across sectoral public policies.

5.2. LADM_COL-POT as an extended model of the LADM_COL core

The LADM_COL-POT profile is conceived as an extended model that specializes the LADM_COL conceptual core for the spatial planning domain. Its design reuses the core elements—parties, rights, restrictions, responsibilities, and spatial units—and adapts them to explicitly represent the rules and instruments specific to territorial planning. In doing so, the LADM_COL-POT profile demonstrates how LADM can be extended to support spatial planning decisions and formalize inter-model business rules between land administration and planning domains (Alvarez et al., 2023).

This profile does not redefine the basic concepts of land administration; rather, it contextualizes them within the regulatory and administrative framework of planning. In this way, land-use zones, urban treatments, building regulations, or territorial determinants are modeled as coherent extensions of the core, maintaining semantic interoperability with other extended models, such as cadastre–land registration or environmental models.

It is worth noting that the construction of LADM_COL-POT was neither immediate nor straightforward. At the time of its development, there was no consolidated methodology for defining extended models of this nature, which required an iterative process of conceptual clarification, scope delimitation, and interinstitutional validation. This process, in turn,

contributed to a more mature understanding of the role of extended models within a model-driven architecture applied to the territory.

5.3. Model governance: scope, institutional roles, and data

The development of LADM_COL-POT made a significant contribution to clarifying governance relationships among the various entities involved in territorial information management. It enabled a more precise differentiation of roles between:

- Institutions responsible for defining data standards and spatial planning policies (such as the Instituto Geográfico Agustín Codazzi—IGAC—and the Ministry of Housing).
- Coordination bodies for the national spatial data infrastructure (the Colombian Spatial Data Infrastructure—ICDE).
- Institutions responsible for creating and maintaining territorial data, primarily municipalities.

This exercise highlighted the importance of clearly delimiting which data form part of the extended model based on their legal and decision-making relevance, and which function solely as reference data or external inputs. This distinction was key to avoiding model overload, preserving semantic coherence, and facilitating institutional adoption.

Furthermore, the modeling process helped formalize responsibilities for the generation, updating, and use of spatial planning information, strengthening ecosystem governance and the traceability of public decisions.

5.4. From extended model to operational materialization

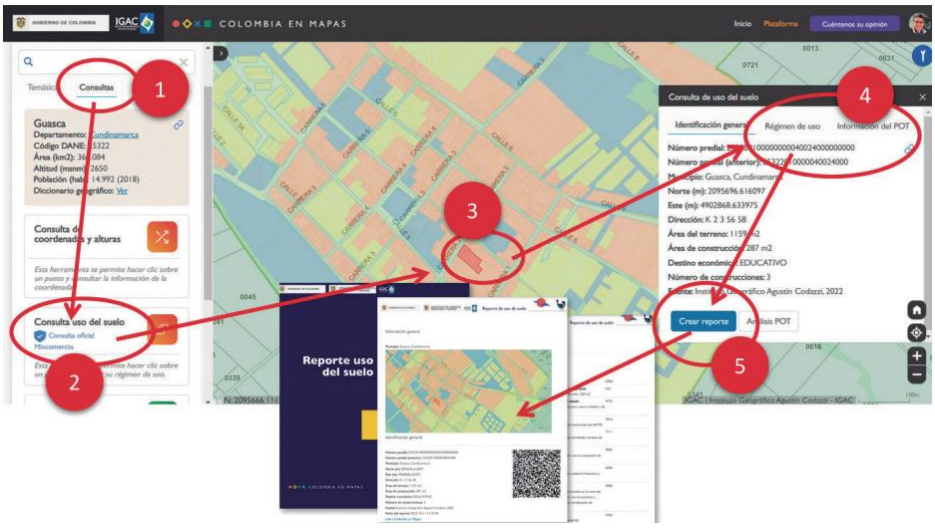
Extended models such as LADM_COL-POT materialized through application models that translate the profile's semantics into concrete functionalities for institutional users and citizens. In the Colombian case, this materialization is already evident in practical implementations, such as:

- Spatial planning geoportals.
- Dashboards for regulatory analysis.
- Simplified query services that enable the cross-referencing of parcel information with land-use regulations.

These applications support functionalities such as issuing land-use certificates, verifying the regulatory compatibility of projects, or providing integrated consultations of territorial restrictions, by explicitly crossing the parcel model (cadastre–land registration) with the legal territorial objects defined in spatial plans (POT). What is relevant in these cases is not the

specific tool used, but the fact that business rules between models are previously structured and formalized within the LADM_COL-POT profile.

Figure 5 Parcel-based spatial planning query and land-use certificate generation in the Colombia OT geoportal



Source: SwissTierras Colombia Project

From the perspective of territorial digital twins, these implementations constitute concrete examples of how a well-defined semantic model enables a transition from visualization to effective decision-making, without relying on ad hoc integrations or isolated developments (Figure 5).

5.5. Business rules, inter-model queries, and digital twins

One of the main contributions of LADM_COL-POT has been the ability to materialize business rules between models, particularly between the parcel domain and the spatial planning domain. By explicitly defining relationships between legal territorial objects in both domains, the model enables inter-model queries that are consistent, repeatable, and auditable.

This approach makes it possible to respond in a structured manner to key public policy questions, such as the compatibility of a proposed use with existing regulations or the identification of restrictions applicable to a specific parcel. These capabilities are fundamental for decision-oriented territorial digital twins, as they allow scenarios and alternatives to be evaluated transparently and in alignment with existing legal frameworks.

5.6. LADM_COL-POT, adjustments toward LADM II, and maturity of the MDA approach

The publication of LADM II will undoubtedly require compatibility adjustments in existing profiles such as LADM_COL-POT. However, the experience accumulated in Colombia

represents a significant added value, having already completed a full cycle of definition, validation, and materialization of extended models within a real institutional environment.

This trajectory has strengthened the maturity of the model-driven architecture (MDA) approach applied to the territory, providing institutional capabilities to manage regulatory changes, evolve models, and adapt implementations without compromising system coherence. In this sense, the transition toward LADM II does not appear as a breaking point, but rather as a natural evolution of an ecosystem that already prioritizes model-based territorial decisions, clear governance, and public value.

6. CONCLUSIONS

1. Territorial digital twins as an evolution of land administration

This paper confirms that territorial digital twins should be understood as an evolution of land administration oriented toward public decision-making, rather than as a mere technological aggregation of data, systems, or platforms. Their value emerges when they integrate information, rules, processes, and governance to support decisions with legal, social, economic, and environmental impacts.

From this perspective, LADM II provides a robust semantic framework to structure this evolution, by formalizing the territory as a system of rights, restrictions, and responsibilities, and by explicitly incorporating traceability and historical versioning as essential elements for public decision-making.

2. Territorial priority and functional convergence with infrastructure

The analysis demonstrates that distinguishing between territorial decisions and infrastructure-related decisions does not fragment public management; instead, it enables more effective and well-governed convergence. Land administration requires models that prioritize the legal and regulatory dimensions of space, while infrastructure models provide the technical detail needed to materialize decisions.

Convergence between both domains should occur at clearly defined minimum points, sufficient to enable coherent decisions, while also allowing bidirectional feedback flows. This approach avoids forced integrations, preserves the semantic integrity of models, and constitutes a key operational principle for decision-oriented territorial digital twins.

3. LADM II, domain rationalization, and alignment with the land management paradigm

LADM II consolidates a modular structure that rationalizes the proliferation of thematic models by grouping them into functional domains aligned with the land management paradigm of use,

tenure, value, and development. This approach reflects a trend similar to that observed in other domains, such as BIM, where semantic governance is essential to sustain interoperability.

Rather than introducing a rupture, LADM II validates approaches that were already being developed through model-driven architectures, providing a common framework that facilitates convergence, international comparability, and the controlled evolution of land administration systems.

4. The Colombian case as a transferable experience

The Colombian experience demonstrates that it is possible to anticipate the principles of LADM II through the definition of a core model, extended models, and application models, supported by a model-driven architecture and clear governance. The development of profiles such as LADM_COL-POT shows how models can materialize intersectoral business rules and enable concrete public decisions, beyond simple information management.

This trajectory is supported by a sustained body of work presented in international FIG forums, documenting the evolution from initial LADM implementation to model-driven extensions and decision-oriented applications (Alvarez & Lemmen, 2016; Alvarez et al., 2018; Alvarez & Wertli, 2019, 2020). Together, these contributions provide empirical evidence of how a model-driven approach to land administration can evolve progressively, strengthening institutional capacities, interoperability practices, and governance mechanisms that are transferable to other national and institutional contexts.

5. From models to ecosystems: an open agenda

Finally, the paper emphasizes that the main challenge for territorial digital twins lies not only in the definition of standards or models, but in their coherent integration within broader ecosystems of domains, layers, and processes. Explicitly incorporating administrative and decision-making processes is as critical as modeling data and territorial objects.

In this sense, LADM II should be understood as an enabler within broader functional architectures, capable of articulating domains, processes, and decisions in a coherent manner. This vision opens a work agenda for the FIG, ISO, and OGC communities, aimed at consolidating territorial digital twins that deliver tangible and sustainable public value.

REFERENCES

ISO 19152:2012 – Land Administration Domain Model (LADM)
International Organization for Standardization. (2012). ISO 19152:2012 — Geographic information — Land Administration Domain Model (LADM).
https://www.iso.org/standard/51206.html

ISO 19152:2024 – Land Administration Domain Model (LADM) Edition II
International Organization for Standardization. (2024). ISO 19152 — Geographic information — Land Administration Domain Model (LADM), Edition II.
https://www.iso.org/standard/83640.html

The first five parts of LADM Edition II have been published as ISO standards now. (2025). FIG Joint Land Administration Conference.
https://ojs.sites.ufsc.br/index.php/fig/article/view/8753

CONPES 4007 (Minvivienda: página con enlaces a “Documento” y “Anexos”)
https://www.minvivienda.gov.co/viceministerio-de-vivienda/estrategia-de-catastro-multiproposito/documento-conpes-4007-del-catastro-multiproposito

LADM Edition II (FIG Working Week 2023 – slides PDF)
https://www.fig.net/resources/proceedings/fig_proceedings/fig2023/ppt/ts08h/TS08H_ISO_LADM_Revision.pdf

Cadastre 2014 and beyond (FIGpub)
https://www.fig.net/resources/publications/figpub/figpub61/

Buenas prácticas (SwissTierras) – Nacionales
http://www.guonderland.com/galex/FIG2026/00_LIBRO_SWISSTIERRAS_COLOMBIA_BUENAS_PRACTICAS_NACIONALES.pdf

Buenas prácticas (SwissTierras) – Territoriales
http://www.guonderland.com/galex/FIG2026/00_LIBRO_SWISSTIERRAS_COLOMBIA_BUENAS_PRACTICAS_TERRITORIALES.pdf

Land administration for sustainable development (Williamson et al., 2010)

Beyond the Land Administration System. Let’s Talk About Land Management! (2023).
Alvarez, G., & Gil Rojas, O. FIG Working Week 2023. International Federation of Surveyors (FIG), Orlando, FL, United States.
https://www.fig.net/resources/proceedings/fig2023/papers/ts09j/TS09J_alvarez_gil_rojas_12083.pdf

From cadastre to land administration: The Colombian experience with LADM.
Alvarez, G., Wertli, J., & Lemmen, C. (2018). In Proceedings of the FIG Congress 2018, Istanbul, Turkey. International Federation of Surveyors (FIG).

Model-driven land administration: Lessons learned from Colombia.

Alvarez, G., & Wertli, J. (2019). In Proceedings of the FIG Working Week 2019, Hanoi, Vietnam. International Federation of Surveyors (FIG).

Interaction of Land Objects from LADM Models to Improve Citizen Services (2023).
Alvarez, G., Bernal Vargas, L., & Albarracín, J. FIG Working Week 2023. International Federation of Surveyors (FIG), Orlando, FL, United States.
https://www.fig.net/resources/proceedings/fig2023/papers/ts03i/TS03I_alvarez_bernal_vargas_et_al_12084.pdf.

The Colombian Land Administration Domain Model: A case study of LADM implementation.
Alvarez, G., & Lemmen, C. (2016). In Proceedings of the FIG Working Week 2016, Christchurch, New Zealand. International Federation of Surveyors (FIG).

BIOGRAPHICAL NOTES

CONTACTS

GOLGI ALVAREZ
Senior International Consultant in Land Management
Cll 22d # 93 - 16 Casa 25 Segunda Etapa
Bogota
Colombia
+57 312 279 6581
galvarezhn@gmail.com

DAVID FRIEDRICH
Team Leader and Business Development Manager Consulting
BSF Swissphoto AG
Alpenstrasse 3
8152 Glattpark (Opfikon)
Switzerland
+41 44 871 22 22
david.friedrich@bsf-swissphoto.com

JOERG WERTLI
CEO
BSF Swissphoto AG
Alpenstrasse 3
8152 Glattpark (Opfikon)
Switzerland

+41 76 405 41 89
joerg.wertli@bsf-swissphoto.com