Formalizing land indicators for SDGs: Implementation and evaluation using international standards

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Key words: ISO 19152 LADM, SDG 1.4.2, Land administration indicators, formalization

SUMMARY

This paper explores the integration of the ISO 19152, Land Administration Domain Model (LADM), with Sustainable Development Goal (SDG) indicator 1.4.2, which focuses on land tenure security and the availability of legal documentation. The primary objective is to design and implement a dynamic database system that represents real-world land administration changes over time, incorporating the complexities of land rights transfers, party relationships, and spatial units. The research leverages PostgreSQL and PostGIS to create a flexible and scalable system capable of managing temporal data and generating SDG 1.4.2 reports.

Through the use of multiple constraints and custom functions, the system ensures data integrity while dynamically tracking changes in land tenure and ownership. Testing was conducted using simulated datasets across three years, which modelled evolving land rights, population changes, and administrative updates. Using a small test data set, the results were validated by comparing manual calculations with the system's automated outputs, demonstrating the accuracy and reliability of the approach.

The findings highlight the potential of using LADM in SDG indicator calculations and demonstrate the system's ability to handle complex, multi-dimensional land administration scenarios. The use of an ISO standard to formalize indicator specification has the benefit of supporting fully automated computation. This functionality goes beyond country level (multi-) year SDG indicator reporting. The approach allows to specify the reporting at any spatial level (e.g. country, province or municipality) and for any time interval (multi-year, year, quarter, month). This allows more fine analysis of the developments, also withing a country and at finer temporal granularity.

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1. INTRODUCTION

Land administration plays a crucial role in achieving the SDGs. Effective land administration provides a framework that enhances agricultural sustainability and socio-economic growth by ensuring the clarity and protection of land rights, thereby reducing land disputes and improving agricultural productivity(Williamson et al., 2010). Monitoring the SDGs is a critical component in assessing global progress toward these goals. However, it faces a number of challenges, such as the lack and inconsistency of data(Tuholske et al., 2021), the gap between localisation and globalisation indicators(J. Chen et al., 2020), and the lack of harmonised monitoring tools. These challenges make it difficult to accurately assess SDGs progress. Formalized and standardised indicators present a robust solution to these issues(Unger et al., 2021). It ensures consistency and clarity in indicator definitions and calculations, enhances comparability across regions and time, improves efficiency through automation, and ensures accuracy in tracking progress towards SDG targets.

In this context, the LADM The ISO 19152 Land Administration Domain Model (LADM) provides a comprehensive framework for land administration, enhancing SDG measurement and monitoring. Its key components, such as LA_Party, LA_SpatialUnit, and LA_RRR, support consistent data collection and analysis (ISO, 2024). The LADM is particularly useful for formalizing and standardizing land-related SDG indicators.

This study explores how the ISO 19152 LADM can support the formalization and standardization of land-related SDG indicators, focusing on SDG 1.4.2. The research aims to validate the LADM framework's ability to optimize indicator calculation and representation, ensuring accuracy and consistency across regions and timeframes. The main research question is: "How can the ISO 19152 LADM be implemented to support the formalization and standardization of land-related SDGs?" This will be explored through subquestions on developing a conceptual model for SDG 1.4.2, translating it into a physical database, and assessing its added value for SDG monitoring.

The rest of this paper is structured as follows: Section 2 reviews the background and related work on land administration and SDG monitoring, emphasizing the role of LADM in standardizing SDG 1.4.2 indicators and ensuring data consistency. Section 3 describes the methodology, detailing the transition from the conceptual model to the physical database, including database schema design, constraints, and computational functions for indicator calculation. Section 4 presents the implementation and validation results, comparing manual and automated calculations, evaluating data integrity mechanisms, and analyzing spatial visualization capabilities across multiple levels and time periods. Section 5 summarizes the findings, highlighting contributions and future work.

2. BACKGROUND

2.1 Sustainable Development Goals

The Sustainable Development Goals (SDGs) were adopted by the United Nations in 2015 as a global development agenda aimed at achieving balanced progress in economic, social, and environmental dimensions by 2030 (United Nations, 2015). The SDGs consist of 17 goals and 169 targets, addressing issues such as poverty eradication, hunger elimination, health and well-being promotion, quality education, gender equality, access to clean water and sanitation, economic growth, reducing inequalities, and climate action (Morton et al., 2017). Unlike the Millennium Development Goals (MDGs), which primarily targeted developing countries, the SDGs are more broadly inclusive and universally applicable, addressing challenges faced by countries at all levels of development.

To effectively monitor and evaluate SDG progress, a comprehensive indicator framework was established. This framework has 17 goals and 169 targets, including 248 indicators (231 unique) categorized into three tiers based on the development of methodologies and the availability of global data (Indicators, 2016). Each SDG indicator comes with a metadata file that outlines key information, including indicator definitions, data sources, collection methods, and comparability with international standards, etc. These metadata files are crucial for guiding data collection and ensuring consistent application of methodologies across contexts. However, differences in detail and update frequency arise due to varying organizational responsibilities.

2.2 Land Administration and ISO 19152 LADM

Land administration involves determining, recording, and disseminating information about land ownership, value, and use to implement land management policies. It encompasses land tenure, land value, land use, and land development. The ISO 19152 Land Administration Domain Model (LADM), an international standard, provides a unified structured framework for land administration to guide the modernisation of land governance systems and to ensure that they meet global standards of efficiency, transparency and equity. The LADM represent the relationships between people and land, widely adopted by international organizations (Enemark et al., 2016) and implemented in several countries (Kalogianni et al., 2021).

Released in 2012 as ISO 19152, LADM Edition I(ISO, 2012) aimed to standardize land administration systems by providing a common language and framework. It is limited to the land tenure component of the land administration paradig. Its primary goal is to ensure interoperability between different land administration systems, allowing various stakeholders to manage and exchange land information effectively. LADM Edition II, which is underdeveloped, intends to extend the scope of Edition I to include land value, land use, and land development. The first part of Edition II was recently published(ISO, 2024).

3. METHODOLOGY

The overall approach of this research follows a structured process that first connects the LADM standard with SDG indicators and then transitions from a conceptual model to a physical implementation. As shown in Figure 1, the conceptual model is systematically mapped to LADM classes, while the physical model is implemented using PostgreSQL and PostGIS, incorporating custom data types, standardized code lists, and integrity constraints. The conceptual model development has been completed (M. Chen et al., 2024) and is not elaborated in this study, with only the final results presented. The core focus of this paper is on the physical implementation, including database structure, computation methods, and system application.

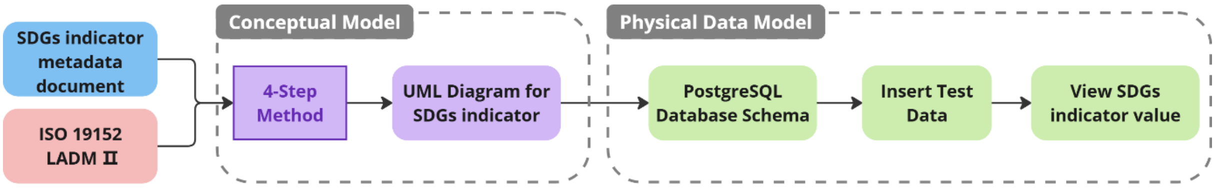

Figure 1. Workflow

In this research, SDG 1.4.2 was selected as an example because it evaluates both legal land tenure security and its alignment with core land administration objectives, while seamlessly integrating with LADM, making it well-suited for structured computation and analysis. The full definition of SDG Indicator 1.4.2 states: *"Proportion of total adult population with secure tenure rights to land, (a) with legally recognized documentation, and (b) who perceive their rights to land as secure, by sex and type of tenure."* Applying the Four-Step Method, the resulting conceptual model is represented in a UML diagram, as shown in Figure 2. (More details refer to the full research study (M. Chen et al., 2024)).

3.1 Physical Model Requirements

The physical model must ensure data consistency, standardization, scalability, and operability. It must maintain data accuracy through comprehensive constraints and validation rules, conform to the ISO 19152 LADM standard for global compatibility, support flexible expansion for future needs, and effectively implement abstract concepts for practical use.

- **Data Consistency**: Ensure data accuracy through constraints and validation rules.
- **Standardization**: Conform to ISO 19152 LADM for global compatibility.
- **Scalability**: Support future data growth and flexible expansion.
- **Operability**: Implement conceptual model concepts for efficient data management.

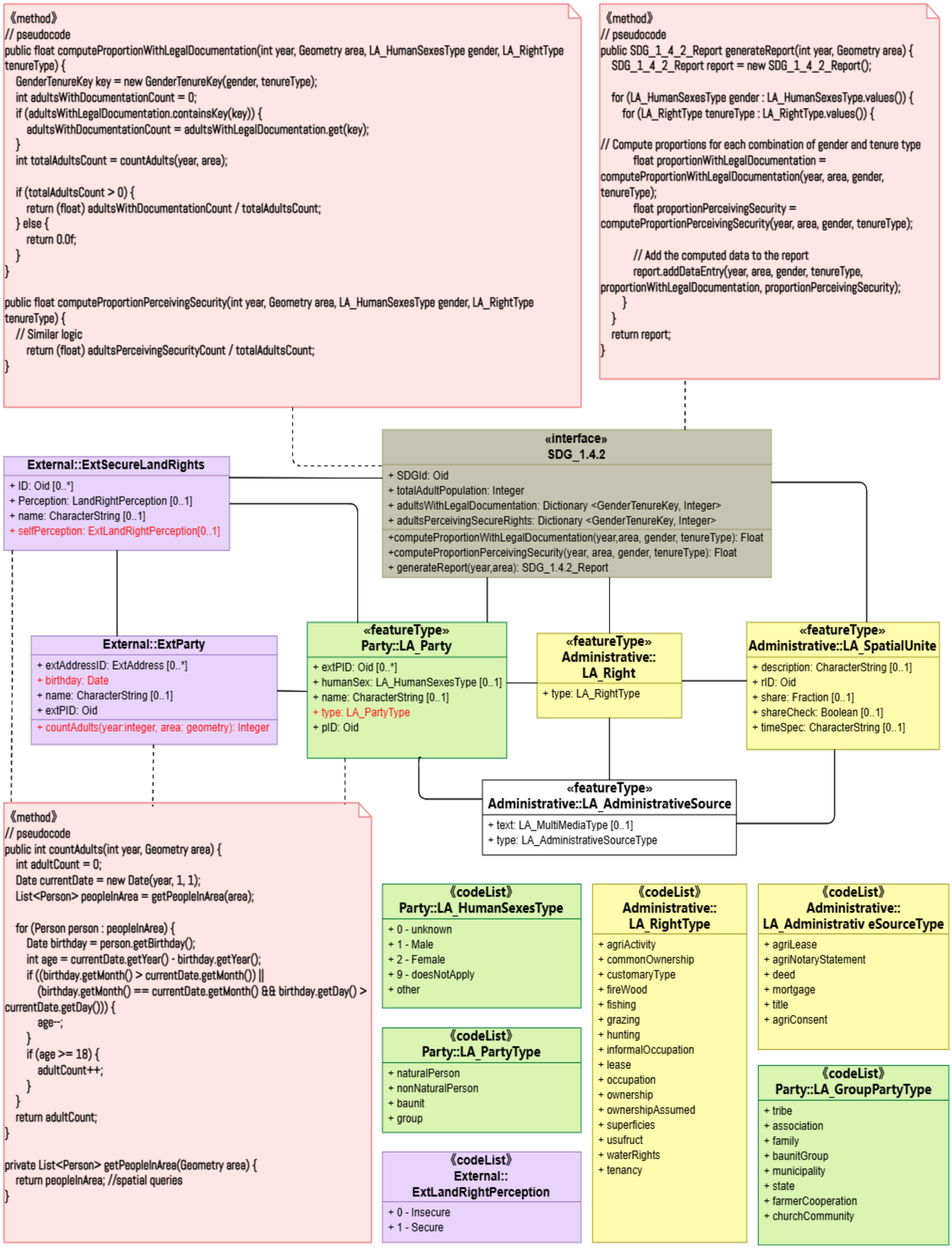

Figure 2. UML Class Diagram for SDG Indicator 1.4.2 Based on the LADM Model.

3.2 Model Transformation Strategy

The physical model is designed by mapping key elements from the conceptual model to specific data structures. Strategies include:

- **Class-to-Table Mapping**: LADM classes (e.g., LA_Party, LA_SpatialUnit) are translated into database tables, maintaining relationships through foreign keys.
- **Attribute-to-Column Mapping**: Attributes of LADM classes are mapped to database fields using standard data types.
- **Normalization**: The model follows normalization principles to reduce redundancy and ensure efficient storage. By decomposing the classes and relationships in the conceptual model into multiple related tables, the physical model ensures data consistency and integrity.
- **Hierarchical Mapping**: Hierarchical relationships (e.g.: versioned objects) in LADM are implemented through hierarchical table structures, ensuring data traceability.

3.3 Maintaining Data Consistency and Integrity

Data consistency and integrity are ensured through:

- **Data Constraints:** Strict database constraints (e.g., primary keys, foreign keys) validate data entries.
- **Hierarchical Data Integrity:** Versioned objects in LADM require managing both historical and current data. Hierarchical table structures in the physical model ensure data traceability and consistency.
- **Transaction Control:** The physical model uses transaction operations to ensure data atomicity and consistency. If an operation (e.g., insert, update, delete) violates integrity constraints, the system rolls it back to maintain data consistency.

3.4 Scalability and Flexibility

The physical model is designed to be scalable and flexible to accommodate future changes in demand:

- **Modular Design**: The physical model is highly modular. Each LADM class or component is treated as an independent module.
- **External Data Integration**: The model supports integration with external data sources through interface classes and foreign key references.
- **Scalability Consideration**: The model uses partitioning tables and optimizing indexing to handle large datasets efficiently.

This framework guides the transition from conceptual to physical models and standardizes land administration systems. It ensures the physical model aligns with international standards and offers flexibility and scalability for future needs. It serves as a foundational guideline for developing robust land information systems.

4. IMPLEMENTATION

This section presents the implementation of the proposed framework, including database design, data processing, and automated reporting. PostgreSQL with PostGIS was used as the primary database management system to ensure spatial data handling, while QGIS were employed for visualization.

The database model is structured to store and process all required information for SDG 1.4.2, including legally recognized documentation, perceived tenure security, and demographic attributes. It integrates LADM components with external survey data, ensuring interoperability and standardization.

4.1 Core Tables from UML Class

In the process of converting UML classes to SQL database tables, each UML class is mapped to a corresponding database table. This transformation is a fundamental step in implementing the physical data model, ensuring that the attributes and relationships defined in the UML model are accurately reflected in the database schema. Typically, a UML class consists of class names, attributes, and cardinalities, which are then mapped to SQL table names, columns, and constraints respectively. Table 1 illustrates how the main components of a UML class translate into SQL database elements.

Table 1. Mapping UML Components to SQL Representations

UML Component	SQL Representation	Example
Class Name	Table Name	UML Class: *LA_Party* → SQL Table: LA_Party
Attribute Name	Column Name	UML Attribute: *name* → SQL Column: name
Attribute Type	Data Type	UML Type: *CharacterString* → SQL Type: TEXT
Multiplicity: 1	NOT NULL Constraint	UML Multiplicity: *1* → SQL Constraint: name TEXT NOT NULL
Multiplicity: 0..1	Allow NULL (No constraint)	UML Multiplicity: *0..1* → SQL Column: name TEXT
Multiplicity: 0..*	Many-to-Many Relationship, Association Table	UML Multiplicity: *0..*** → Requires a **join table**
Unique Identifier	PRIMARY KEY Constraint	UML Attribute: *pID* → SQL: pID INTEGER PRIMARY KEY
Inheritance *(usually in italics in the upper right corner)*	INHERITS keyword *(PostgreSQL specific)*	UML: *LA_Party* inherits VersionedObject → SQL: INHERITS (VersionedObject)

Visibility *(public/private/protected)*	Ignored in SQL, all attributes accessible	N/A
Initial Value	DEFAULT Clause	UML *availabilityStatus*: availabilityStatusType = documentAvailable → SQL: availabilityStatus INTEGER DEFAULT 1 *(where 1 is the ID for documentAvailable)*

The database consists of six key tables, which are derived from UML classes. The *LA_Party* table stores information on individuals or organizations holding land rights, with attributes such as age and gender for disaggregated SDG analysis. The *LA_RRR* table captures land rights, restrictions, and responsibilities, linking land tenure claims to parties. The *LA_Source* table contains legally recognized documentation supporting land tenure rights. The *ExtPartyPerceiveSecureLandRights* table records perceived security responses collected from external surveys, providing a complementary perspective to legal tenure security. *ExtParty* maintains external party information, allowing for external datasets, such as census records, to be linked to the land administration system, enabling interoperability with external data sources.

To illustrate how UML classes are implemented as relational tables, *LA_Party* serves as an example. As shown in Figure 3, the UML model defines attributes such as pID, extPID, name, humanSex, and type, which are mapped directly to corresponding SQL components.

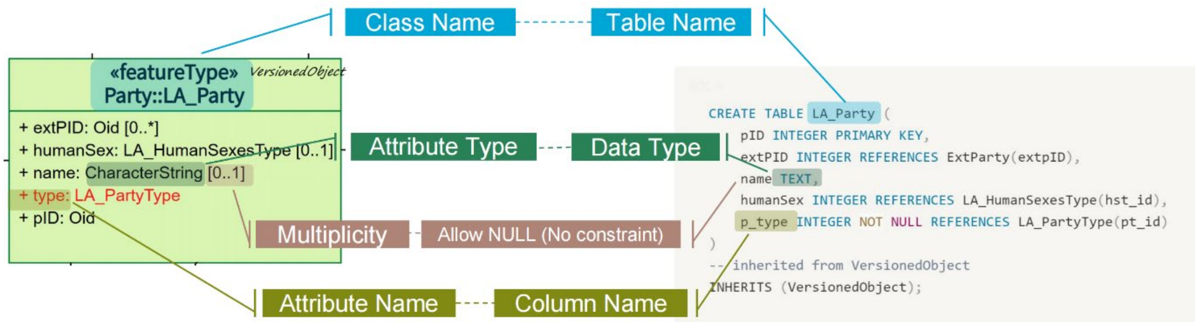

Figure 3. Mapping UML Class *LA_Party* to SQL Table Structure

- **pID** is implemented as INTEGER PRIMARY KEY, ensuring uniqueness.
- **extPID** is a **foreign key** referencing *ExtParty*(extPID), capturing **many-to-many relationships**.
- **humanSex** is a **foreign key** referencing *LA_HumanSexesType*(hst_id), linking parties to a **gender classification list**.
- **p_type** is defined as NOT NULL, referencing *LA_PartyType*(pt_id), ensuring each party is assigned a predefined category.

4.2 Relationships Between Tables

The relationships between tables in the database reflect Inheritance and Association structures from LADM, ensuring data integrity and efficient query execution. Inheritance is implemented using the *VersionedObject* table, which provides bi-temporal attributes such as *beginLifespanVersion* and *endLifespanVersion* to track system and real-world time changes. Tables like *LA_Party, LA_RRR, and LA_Right* inherit from this structure, ensuring consistent temporal data management. Associations are implemented through foreign key constraints, linking *LA_RRR* to *LA_Party* for party-land right relationships, *LA_RRR* to *LA_Source* to verify legal documentation, and *ExtPartyPerceiveSecureLandRights* to *LA_Party* for perceived tenure security. In cases of many-to-many relationships, such as *extaddress* and *LA_SpatialUnit*, a join table maintains referential integrity. These relationships ensure logical consistency, prevent orphan records, and allow seamless data retrieval for SDG 1.4.2 computations.

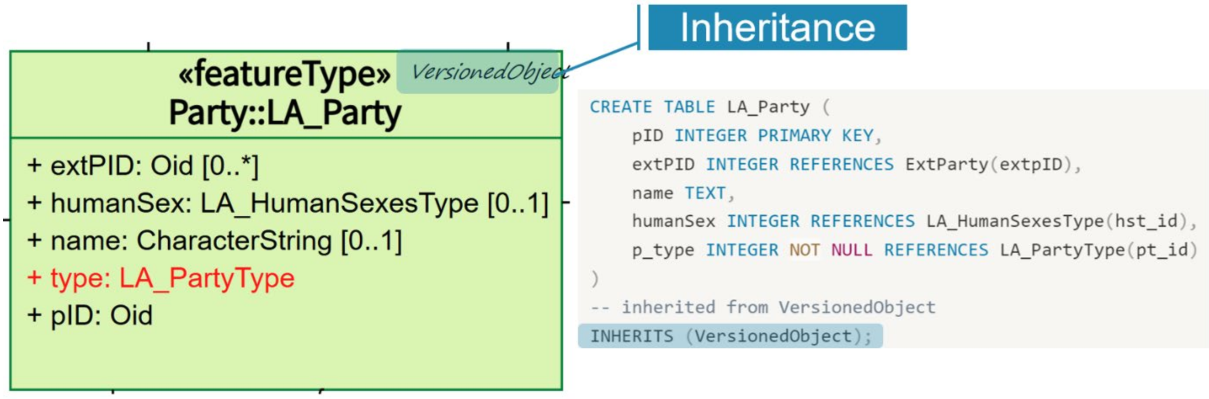

Figure 4. Inheritance Mapping from UML Class *LA_Party* to SQL Table Structure

4.3 Code Lists and Data Types

Code lists define enumerated values for attributes related to land tenure rights, documentation, and party classifications. In the database, they are implemented using reference tables with predefined values. For instance, the *LA_RRR* table includes a field for tenure type, which references the *LA_RightType* table containing values such as ownership, leasehold, customary tenure, and informal use rights. These reference tables prevent inconsistent or arbitrary data entries while enabling standardized queries and reporting. To enforce integrity, foreign key constraints were applied, like to ensure that any land tenure record in *LA_RRR* can only reference a valid tenure type from CodeList *LA_RightTyp*.

Custom data types were introduced to support specialized attributes that are not natively handled by PostgreSQL. For example, the *Fraction* type was implemented to represent ownership shares, ensuring that land tenure rights allocated among multiple parties always sum to 1. This type is defined using a *CHECK* constraint to prevent negative values or ownership percentages exceeding 100%, thereby maintaining logical consistency in tenure records.

4.4 Constraints

The database enforces three types of constraints to maintain data integrity and prevent inconsistencies. (1) Primary keys (PKs) and foreign keys (FKs) ensure unique identification and enforce relationships between tables, such as linking *LA_RRR* to *LA_Party* and *LA_Source*. (2) *CHECK* constraints validate data, such as restricting Fraction values between 0 and 1 for ownership shares. *NOT NULL* constraints prevent missing critical attributes, ensuring completeness. *UNIQUE* constraints avoid duplicate entries in key attributes like document IDs.

Figure 5. Example of Constrains in SQL

(3) Triggers and functions enforce complex constraints by automating validation and maintaining logical consistency. For example, the *check_fraction_constraint()* function, executed through a *BEFORE INSERT OR UPDATE* trigger on *LA_RRR*, ensures that the total ownership fraction for a parcel never exceeds 1, preventing invalid land tenure allocations. The *validate_versioned_object()* function enforces temporal constraints on *VersionedObject*, ensuring that *endLifespanVersion* is always later than *beginLifespanVersion*, preserving historical accuracy. Additionally, the *validate_party_rights()* function, triggered on *LA_Right*, prevents records from referencing non-existent parties, maintaining referential integrity. These automated mechanisms enhance data reliability and prevent errors before transactions are committed.

4.5 Computation of SDG 1.4.2

The computation of SDG 1.4.2 indicators relies on several database functions that filter, count, and categorize land tenure data dynamically. These functions ensure accurate data extraction, integrating spatial constraints, temporal validity, and demographic classifications. The key functions include:

- *countAdult*: Calculates the total adult population within a defined geographic area and time period, ensuring proper SDG compliance.
- *computeProportionWithLegalDocumentation*: Computes the proportion of adults holding legally recognized land documents, categorized by gender and tenure type.
- *computeProportionPerceivingSecurity*: Calculates the proportion of adults who perceive their land tenure as secure, using external survey data.

```sql
CREATE OR REPLACE FUNCTION countAdults(CA_begindate DATE, CA_area GEOMETRY)
RETURNS INTEGER AS $$
DECLARE
    adultCount INTEGER := 0;
BEGIN
    SELECT COUNT(*) INTO adultCount
    FROM (
        SELECT DISTINCT ON (e.extpid) e.extpid
        FROM extparty e
        JOIN extaddress_suid_relation esr ON e.extaddressid = esr.extaddressid
        -- Ensure that the address is within the given geographical area
        WHERE ST_Contains(CA_area, esr.suid_geom)
        -- Calculation of the age of the adult, based on the date of commencement
        AND EXTRACT(YEAR FROM age(CA_begindate, e.birthday)) >= 18
        -- Timeframe for checking census records
        AND (e.enddate IS NULL OR e.enddate >= CA_begindate)
        AND e.begindate <= CA_begindate
    ) AS unique_adults;

    RETURN adultCount;
END;
$$ LANGUAGE plpgsql;
```

Figure 6. Example of SQL Implementation for the *countAdults* Function

Instead of storing precomputed results, the *SDG_1_4_2_Report* view dynamically joins these datasets and applies aggregate calculations by region and year. This ensures that any updates to land tenure records or perceived security data are immediately reflected in the computed indicators, eliminating redundancy while maintaining data integrity. Additionally, conditional queries handle missing values to prevent incomplete records from distorting results. This approach provides an efficient and scalable method for real-time SDG monitoring and policy assessment.

5 INDICATOR REPORTING

To test the implementation, a synthetic dataset was generated, simulating three years of land tenure transactions and survey responses. The dataset includes various ownership structures, demographic distributions, and changes in perceived tenure security over time.

5.1 Validation and Error Handling

Validation was conducted through manual cross-checking, where indicator calculations were compared against expected results to confirm accuracy. Several edge cases were tested, including scenarios where individuals lacked legal documentation but reported tenure security. These cases ensured that the model correctly distinguished between formal and informal tenure recognition.

Error handling mechanisms were implemented to prevent inconsistent or incomplete data entries. A constraint function blocks negative values in the Fraction type, ensuring that land ownership percentages remain within valid bounds. Foreign key constraints prevent orphan records, ensuring that every land right corresponds to a valid legal document. Temporal constraints in VersionedObject enforce logical sequencing of land tenure transactions.

5.2 Indicator Results and Consistency Checks

To ensure the accuracy of the SDG 1.4.2 computation, the results generated by the database were manually cross-checked against expected values calculated independently. A subset of records from the synthetic dataset was selected, and the values for *computeProportionWithLegalDocumentation* and *computeProportionPerceivingSecurity* were computed manually using the formulas defined in the SDG metadata. After running multiple test cases, the manually calculated indicator values were found to be identical to those returned by the database view, confirming the accuracy of the SQL computations. The final computed values, as generated by the *SDG_1_4_2_Report_view_2002_all* view, are displayed below:

	report_begindate timestamp with time zone	report_enddate timestamp with time zone	report_ geome	report_category text	report_subcategory text	report_totaladultscount integer	report_proportionperceivingsecurity double precision	report_proportionwithlegaldocumentation double precision
1	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	gender	Male	19	0.21052631578947367	0.42105263157894735
2	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	tenure_type	ownership	19	0.47368421052631576	0.42105263157894735
3	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	gender	Female	19	0.2631578947368421	0.21052631578947367
4	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	gender	doesNotApply	19	0	0
5	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	tenure_type	lease	19	0	0.21052631578947367
6	2002-01-01 00:00:00+01	2003-01-01 00:00:00+01	01030000...	total	[null]	19	0.47368421052631576	0.631578947368421

Figure 5. Final Report View within the Complete Test Area in 2002

5.3 Spatial Visualization and Reporting

The spatial visualization of SDG 1.4.2 indicators enables multi-level, temporal, and categorical analysis, facilitating a deeper understanding of land tenure security trends. The system supports different geographic levels, including national, regional, and local parcel-based visualizations. As shown in Figure 6 (a), multi-level mapping allows for hierarchical analysis, where users can zoom in from broader regions to individual land parcels. Figures 6 (b) and (c) illustrate disaggregated visualization, focusing on female tenure security at different administrative levels. The flexibility to visualize tenure security data at varying spatial scales helps in identifying localized disparities.

Temporal visualization enables users to compare different years, tracking changes in tenure security and legal documentation rates over time. Additionally, filtering by attributes such as gender and tenure type supports targeted policy analysis. This approach ensures that SDG 1.4.2 monitoring is dynamic, scalable, and policy-relevant.

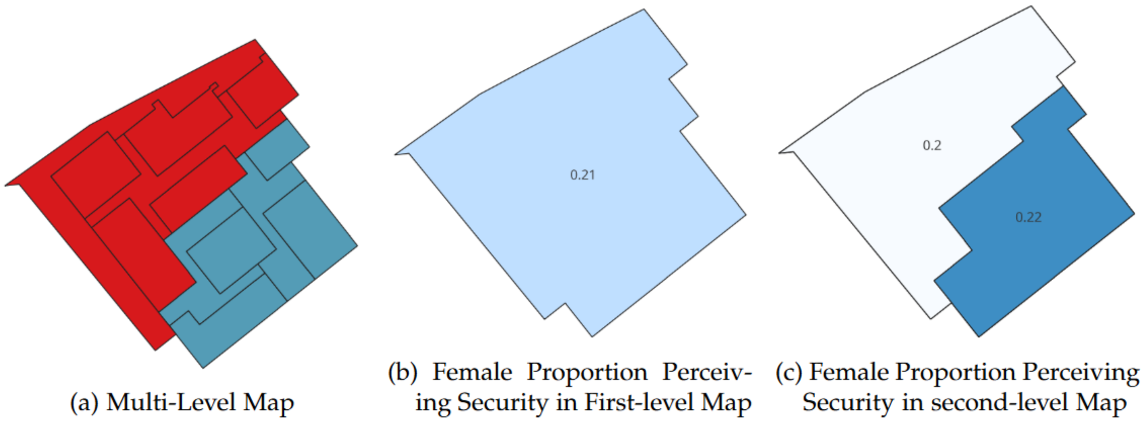

Figure 6. Multi-level Governance SDG Report Visualization

6 CONCLUSION

This research developed and evaluated an LADM-based land administration system for monitoring SDG Indicator 1.4.2, focusing on a standardized database architecture for dynamic and automated indicator computation. The study followed a structured approach, including conceptual modeling, system implementation, and validation, to assess its feasibility for real-world applications.

The system was designed using ISO 19152 LADM, with a relational database in PostgreSQL/PostGIS integrating core land tenure entities. Custom functions and triggers ensured data consistency, managing ownership fractions, bi-temporal validity, and land rights history. The SDG_1_4_2_Report view dynamically computed SDG indicators, reducing redundancy and enabling real-time monitoring. A synthetic dataset simulating three years of tenure transactions validated system accuracy, confirming that automated computations matched manual calculations.

This research contributes to standardized SDG monitoring, providing a scalable, automated framework for tenure security assessment. It enhances efficiency and accuracy, reducing reliance on manual data collection. However, limitations include synthetic test data, a single administrative context, and a focus on SDG 1.4.2, limiting generalizability to other indicators or legal systems.

Future work should extend the model to other land-related SDG indicators (e.g., SDG 11, SDG 15) and validate it with real cadastral datasets from different regions. Further improvements include user-friendly interfaces, advanced visualization tools, and multi-user support to enhance practical usability. Optimizing query performance and cloud deployment could improve scalability for large-scale applications. These advancements will further strengthen the system's role in global land administration and SDG monitoring efforts.

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BIOGRAPHICAL NOTES

Mengying Chen holds an MSc in Geomatics from Delft University of Technology and a BSc in Geographic Information Science from Wuhan University. Her research focuses on integrating the Land Administration Domain Model (LADM) with Sustainable Development Goals (SDGs), particularly in formalizing land tenure security indicators.

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