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The Application Domain Extension (ADE) 4D Cadastral Data Model and Its Application in Turkey

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Abstract: The 3D cadastre, one of the most fundamental components of the 3D LAS (Land Administration System), aims to provide an integrated 3D view of legal (Right, Restrictions, and Responsibilities–RRR) and physical boundaries in multi-storey properties; therefore, to extend the flexible and modular basis of LADM, which best represents legal boundaries and RRRs, some integrated models using technical standards (e.g., CityGML, IFC, InfraGML) are developed to represent the full 3D cadastre. However, since most of the developed 3D integrated data models are designed at the conceptual level, there is a knowledge gap in logical data model relationships, which is the next processing step in the fully integrated 3D data model stage. The main argument of this study is an innovative ADE 4D Cadastral Data Model to represent 3D cadastral objects registration with time attributes using LADM and CityGML. The data management and organization are done in an open-source database for the Turkish cadastral system. This research will discuss two main topics. The first is how to implement a suitable way of realising LADM-based 3D cadastral object registration by focusing on developing the presentation of those cadastral objects to 4D (3D + t), with time attributes in alignment with the jurisdictional framework in Turkey. The second is how the data is managed in an open-source PostgreSQL database. In addition, the usage type of cadastral objects is shown in a CesiumJS, a visualisation platform. Moreover, this study will contribute to eliminating the knowledge gap between the conceptual and logical models.

Keywords: 3D–4D cadastre; LADM; CityGML; 3D database management system; PostgreSQL; 3D visualizations

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1. Introduction

The Cadastral Systems are considered the core of LASs (Land Administration Systems), including the individual parcels recording interests (RRRs) above/below/on land and water surface; however, the current LASs are still 2D-based, which usually represents and records the footprint of the 3D reality of multi-story buildings. The complexities in the current 3D cities have driven the development of 3D cadastres. Moreover, the concept of the third dimension is introduced in the domain [1–5]. It is challenging to properly register the legal boundaries and RRR related to private, communal, and public properties [5]. In recent decades, a 3D cadastre has been defined as a system in which condominiums and owners' rights, restrictions, responsibilities (legal models) correspond to progressive policies, standards, and physical models [6–9]. A well-formed and sustainable 3D cadastre will help many other applications such as urban planning, real estate valuation, and construction activities [3,10–12]. Creating a 3D cadastre involves many stakeholders such as land registries, municipalities, institutions, universities, land surveyors, architects, notaries, contractors, owners, and property management companies. Different stakeholders produce many cadastral data. Several activities related to registration, organisation, and visualisation of 3D data are ongoing internationally [5]. The FIG best practices publication on 3D cadastral information modelling [5] discusses the possibilities of linking 3D legal RRR spaces, modelled with LADM (Land Administration Domain Model, ISO19152, 2012), with the physical reality of 3D objects described with CityGML, IFC (The Industry Foundation Classes), InfraGML.

In light of this, many researchers have been claimed that BIM (Building Information Model) and GIS (Geographical Information Science) are suitable for 3D cadastre and visualisations. The reason is that IFC data models and CityGML are good sources for capturing data that have detailed geometry and semantics for 3D cadastral registration [4,10,12–14]. The standards represent legal and physical attributes such as LADM, CityGML, BIM/IFC associated with cadastral studies. Although LADM represents the legal side of cadastral objects, CityGML and IFC are not as successful as LADM in representing RRR between real estate and its owner in the cadastral system [15,16]; therefore, the scope of CityGML, IFC, and LADM are slightly different in terms of concepts representing building elements. Nevertheless, they could also be related, primarily representing objects in the 3D LAS (Land Administration System) such as cadastre, planning, and valuations. BIM (IFC) and 3D GIS (CityGML) could be widely used in cadastre, although they have been independently designed and developed to serve different purposes. In particular, BIM applications focus on all building elements and technical details of the building depending on the scale of a building. At the same time, CityGML is used for a 3D city model or larger-scale applications; therefore, integrated data models between LADM, BIM (IFC), and 3D GIS (CityGML) are the foundation of much academic research carried out worldwide [1,8,14,17–21]. Due to the technological advances in the GIS domain, 3D cadastral developments have grown in terms of properly storing, analyzing, and visualizing 3D objects [10,12,22,23]. Among these studies, the Netherlands comes first in terms of holding the 3D cadastral record [24]. Following the studies done in the Netherlands, a 3D cadastral prototype was developed to support urban planning and management in Shenzhen, China [25,26]. In addition to these studies, many academic studies have also been carried out. At the forefront of these academic studies is developing physical models for 3D cadastre in the Australian states of Queensland and Victoria [3,6,16,18,27,28]. Greece and Sweden are taking essential steps to switch to 3D cadastre. While researching the environmental impact of 3D public law restrictions in Greece [29], studies were being done to convert 2D analogue cadastral boundary plans into 3D digital information and visualization in Stockholm, Sweden [30].

The primary motivation for this research is to introduce an open-source 4D (3D + t) database, which is integrated with LADM, and is CityGML model compliant, and to analyze the existing cadastral system in Turkey using a visualization platform such as CesiumJS. In response to the need for the redevelopment and alignment of international and national standards, the current paper addresses the full 4D cadastral model, represented cadastral objects, legally and physically for the Turkish cadastral system using accepted standards according to ISO and OGC. In this context, the study investigates the necessity of modelling and managing the cadastral objects in the current system by representing the legal and physical aspects in the most compatible way. It is intended to bridge that gap by giving an overview of associations between the conceptual and logical data model by introducing the developed integrated model and storage, in an open-source 4D database, into the transactions with modelling cadastral objects (parcel, building, and independent section) and their interests (RRR). The originality of the study stems from the use of open-source software and platforms, and the novelty of the database allows associating LADM classes with CityGML classes by creating a new class that is not an attribute. Thus, the study provides guidelines for both institutions in Turkey and researchers working on this subject by considering all process steps such as model development, database management, and visualization.

The remainder of this paper is structured as follows: Section 2 is methodology. Section 3 presents the creation of a 4D cadastral data model for Turkey. In addition, how to model cadastral objects' legal and physical attributes according to the registration system in Turkey is explained. Section 4 introduces the newly developed open-source 4D database system and describes the visualization of the new integrated model using an open-source platform. The final section concludes the presented work.

2. Methodology

This paper has researched legal and physical data modelling and presentations for the 4D (3D + t) cadastral transition. The study consists of three main parts: data modelling, data management, and visualization.

- For the first part of the study, the LADM–CityGML integrated data model was chosen as the method. LADM is the best and most widely used ISO data standard for modelling legal data. In addition, another important reason for choosing LADM is that LADM enables the creation of a common ontology in the international platform due to its widespread use. Although CityGML was chosen especially for representing the physical side, different standards such as IFC, IndoorGML, LandXML, and GeoJSON are also available; however, CityGML is the most widely used data standard in collecting 3D data in all public institutions in Turkey. As a result, it was thought that both data collection and sharing will be easier. Details on the development of the model are described in Section 3.
- The basic principle of the second step in the study is the use of open-source software and platforms in managing and visualizing data; therefore, PostgreSQL, which is both widely used for its high processing capacity and open-source database management system, was chosen for data management. The disadvantage of the integrated data model chosen for the study is that the integration of CityGML with LADM is not very practical, and takes time due to its very comprehensive and complex data structure. In addition, there are still problems in transferring the model to the database since the normalization principles of the developed conceptual data model do not fully comply with the database principles. This study ensured that this limitation was eliminated by normalizing the conceptual model and applying it to the database. Section 4 contains the necessary explanations for the second step.
- The final step in the study is visualization. An open-source platform, CesiumJS, was used for the visualization process. As a result of the visualization, the testability of the model became easier. Section 4 also explains the details of the visualization process.

The 4D cadastre, developed with all the processing steps, answers the question of how the Turkish cadastral system should be modelled using international standards within the scope of the 4D cadastre, data management, and visualization.

2.1. LADM

ISO/TC211 accepted LADM in 2012 to standardise cadastral objects' geographical information and geo-characteristics [31]. The primary function of LADM is to create a common ontology in an international framework for the concepts that make up the 3D cadastre that contributes to Land Management Systems (LAS). As a result of this fundamental contribution of LADM, it is easier to understand the cadastral systems of different countries on the international platform [32]. LADM consists of three main packages and one sub-package. They are the LA_Party (Party package), the LA_AdministrativePackage (Management package), the LA_SpatialUnitPackage (Spatial Unit package), and the LA_SurveyingAndRepresentation (Sub-package). The VersionObject class in LADM arranges time information. These packages in LADM, (except for the AdministrativeSource and SpatialSource class), are designed to inherit time information from the VersionedObject class. Time information is designed as the start and end for each class. The start is defined as the start-lifespan version and the end as the end-lifespan version [33]; however, due to the limited 3D support in its current version, LADM II revision work has begun, and it is aimed to be completed in 2023. The LADM II version aims to use different standards (BIM/IFC, CityGML, LandXML, InfraGML, IndoorGML, RDF/linked data, GeoJSON, and INTERLIS) to improve geometric and topological properties [17,34,35]. In addition, 3D spatial profiles such as real estate valuation and spatial planning are developed in the new version for extra information.

Thus, the new version will gain functionality geometrically and temporally for cadastre and land information management systems [11,35].

2.2. CityGML

CityGML is the most comprehensive semantic information model represented in an XML-based format to facilitate the exchange, sharing, storage, and maintenance of the virtual 3D city models. There are two versions of CityGML which have GML application schema: the official 2.0 version, and the 3.0, which is an evolution of the previous versions. CityGML can be extended to represent basic entities, attributes, and associations of 3D city models viewed geometrically, semantically, and topologically [36,37]. CityGML consists of two data modules, which are core and thematic expansion modules. The core module defines the abstract base classes of the CityGML data model, in which thematic classes are derived. The thematic module of CityGML provides thirteen distinct thematic areas for the virtual 3D city model. They are Appearance, Bridge, Building, CityFurniture, CityObjectGroup, Generics, LandUse, Relief, Transportation, Tunnel, Vegetation, WaterBody, and TexturedSurface [38]. Although CityGML is mostly utilised to structure and represent physical parts such as walls, roofs, curbs, or vegetation objects, it is not suitable for representing the corresponding legal extents. For this purpose, legal fields can be represented by expanding the model as a result of the Application Domain Extensions (ADEs) which are designed in CityGML [37]. ADE is a mechanism that allows model expansion by incorporating new attribute types, geometries, and associations into the existing model for requirements not available in CityGML [3,39]. Furthermore, CityGML allows multiple representations of city objects on semantic surfaces based on five different levels of detail (LOD), to accurately represent them from the simplest level (LOD1) to the most detailed level (LOD4) [38].

3. Creating a 4D Cadastral Data Model for Turkey

In this sense, the innovative ADE consists of four essential steps. First, the Turkish cadastral system was analysed using the qualitative research method and was modelled within the scope of LADM. The second step is developing a new integrated data model to represent cadastral objects' legal and physical details with high position accuracy. For this phase, physical details corresponding to the legal attributes' information, modelled with LADM, are linked with CityGML through a new ADE. In the third step, the integrated LADM–CityGML model that has been developed is transferred to the new, 4D database created using PostgreSQL, to visualise the cadastral information at the building level. The final step is visualization in the CesiumJS platform and temporal analysis on a city scale. Although some basic concepts of Turkey's integrated 3D cadastral model have already been explained in earlier papers [7,20], this study has improved these concepts with regard to the 4D database, visualization, and time information examples that have been developed.

3.1. Registration System in Turkey

The legal basis of the Turkish cadastral system is the Civil Code, the Cadastre Law 3402, and Condominium Law. The Turkish cadastral system's basic unit is the parcel registered in 2D. According to cadastral law, parcels, independent sections, and real rights must be registered in the title. Since the utility and transportation networks are not registered in the land registry, the parcel, building, and independent sections are seen as cadastral objects. Although the parcel registration is done according to cadastral law, the independent sections' registration is subject to condominium law [40,41]. Moreover, despite the fact that each independent section in a building is the property of its owner, shared areas (elevator, stairs, and car parks) are within the scope of cooperation. In Turkey, the Constitution does not sufficiently detail the boundaries of the third dimension. According to the Turkish Civil Code, the property's boundaries right on the parcel are limited to a certain depth and height (Figure 1).

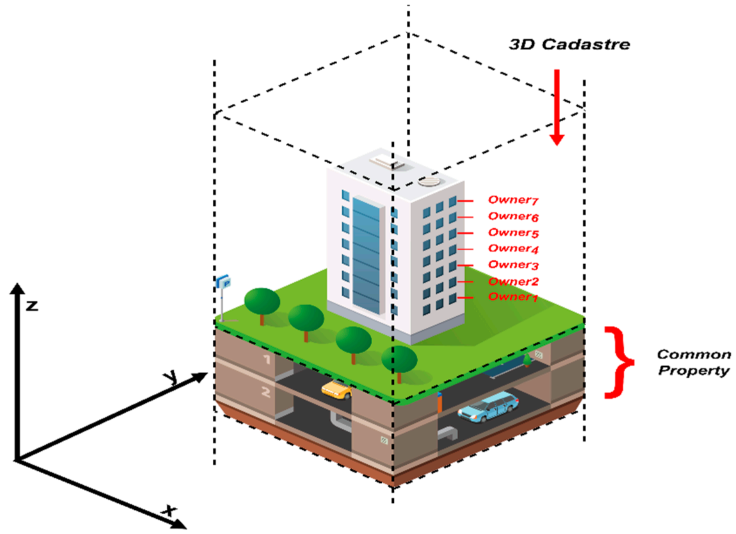

Figure 1. Illustrates the 3D property use.

However, some rights in the Turkish Constitution (for example, right of easement, right of usufruct, right of passage, mortgage) are used to limit this height and depth; therefore, these real rights are associated with applying the third dimension. However, information about real rights is registered as textual in the annotation of the title, and two-dimensional graphic representation is largely possible. Details about the registration procedures in the Turkish cadastral system are available in our earlier papers [20,40], which were used to create Table 1. Table 1 presents the classification of rights defined by Civil law as RRR.

Table 1. Shows the general explanation of the RRR used in the Turkish registration system according to Civil Law.

RRR	Definition
Right	*It is the person's right to use, benefit, and dispose of their real estate according to its legal status. For individuals, this right is divided into two fundamental rights types: Property Right and Limited Real Right, which provides partial use. The limited real rights consist of Mortgage and Easement.*
Restriction	*It is a situation whereby using some real rights restrict property right. These real rights, seen as restrictions, can be listed as Representations, Rights, and Liabilities, Annotations, Mortgages and Easement.*
Responsibilities	*These are the obligations that Right-holders must fulfil regarding their real estate, such as maintenance, repair, and tax.*

In Turkey, cadastral data, including time information (start date and time), is maintained by the GDRLC (General Directorate of Land Registry and Cadastre). From the point of view of Cadastre Law, the time registration of cadastral data includes three types of choices (Figure 2). The first one is Timestamp: it is the time when the registration process is registered together with the registration date and time (start date and time = min). The second one is Period: the historical status given when registering transactions in a specific time period (start date and time = min and delete date and time = tmax), such as a mortgage and easement rights. The last one concerns all transactions, such as buying related to real estate, which must have both begin date and time (tmin) and the end date and time (tmax) recorded [33].

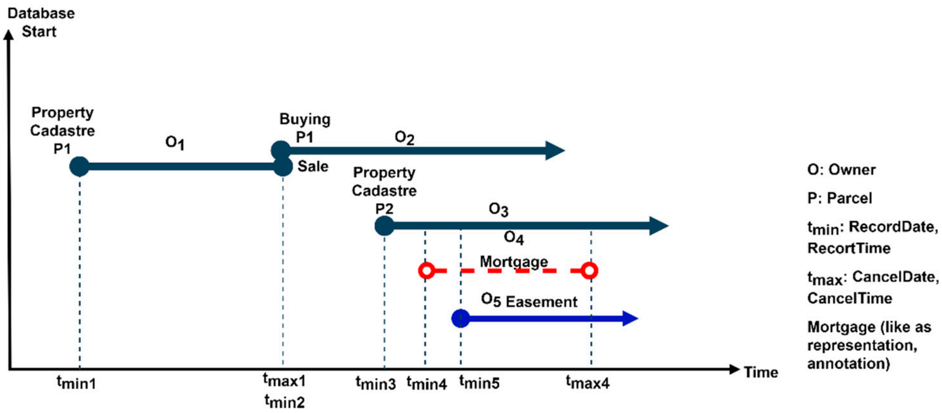

Figure 2. The graphical representation of the transactions of real estate in the Turkish cadastral system over time.

3.2. Developing LADM Based Model for Turkey

The boundaries, geometry, owner, and ownership information of cadastral data change over time. In this case, changes in the cadastral systems should be followed using a temporal scale. Integrating time data into cadastral systems will make it easier to track changes over time. The proposed new 4D cadastral legal model (shown in Figure 3), based on LADM, represents 3D legal objects and connects time attributes with the Turkish cadastral system's concepts. The integration of LADM representing legal objects was used to develop the conceptual model based on the current legal regulations. The rights defined by the by-laws have been classified and adapted to LADM standards. These rights correspond to the RRR class in LADM. Stakeholders in the cadastral system and registered cadastral objects are represented in the party class and the spatial unit class, respectively.

The party package (TR_Party, TR is meaning of Turkey Republic) is a class of ownership that corresponds to the Turkish cadastral system's LADM Party class. The information of all stakeholders associated with real estate in the cadastral system is represented in the TR_Party class. TR_PartyType represents naturalized persons and their legal standing. According to the Turkish legal system, all specified attributes (such as father's name, birthplace, and so on) in the title must be shown by the naturalized person; however, the tax number is sufficient for person who is legally in Turkey. Therefore, the naturalized person must be identified with more detailed information in the party package. In situations where more than one person has the same, or a particular share, of real estate is represented by the Group party. Lastly, TR_PartyRoleType includes various roles, such as owner, institutions, local authority, and professional organisations.

TR_RRR is an abstract class with three sub-classes TR_Right, TR_Restriction, and TR_Responsibility. The right class includes transaction information regarding the property owner, such as purchase, sale, rent. The TR_Right class also has two sub-classes, which are mortgage and easement. The mortgage is both a type of right and restriction. As can be understood from the mortgage class, some rights and restrictions may overlap. The restriction (TR_Restrictions) class consists of four sub-classes: TR_Representations (Beyanlar in Turkish), TR_RightsandLiability (Hak ve yükümlülükler in Turkish), TR_Annotations (Şerhler in Turkish), and TR_Mortgages in the land register. The real estate's transaction information, such as the subject of the transaction, the page number of the land registry, and the document number, are registered in the land registry called Representations. The mortgage class takes part in the right and restrictions class, which has required information for real estate collateral for a possible debt. The annotation class contains information about any situation related to real estate. The Rights and Liabilities class is where rights such as easement, usufruct, right of access, and timeshare property rights are registered to the land register.

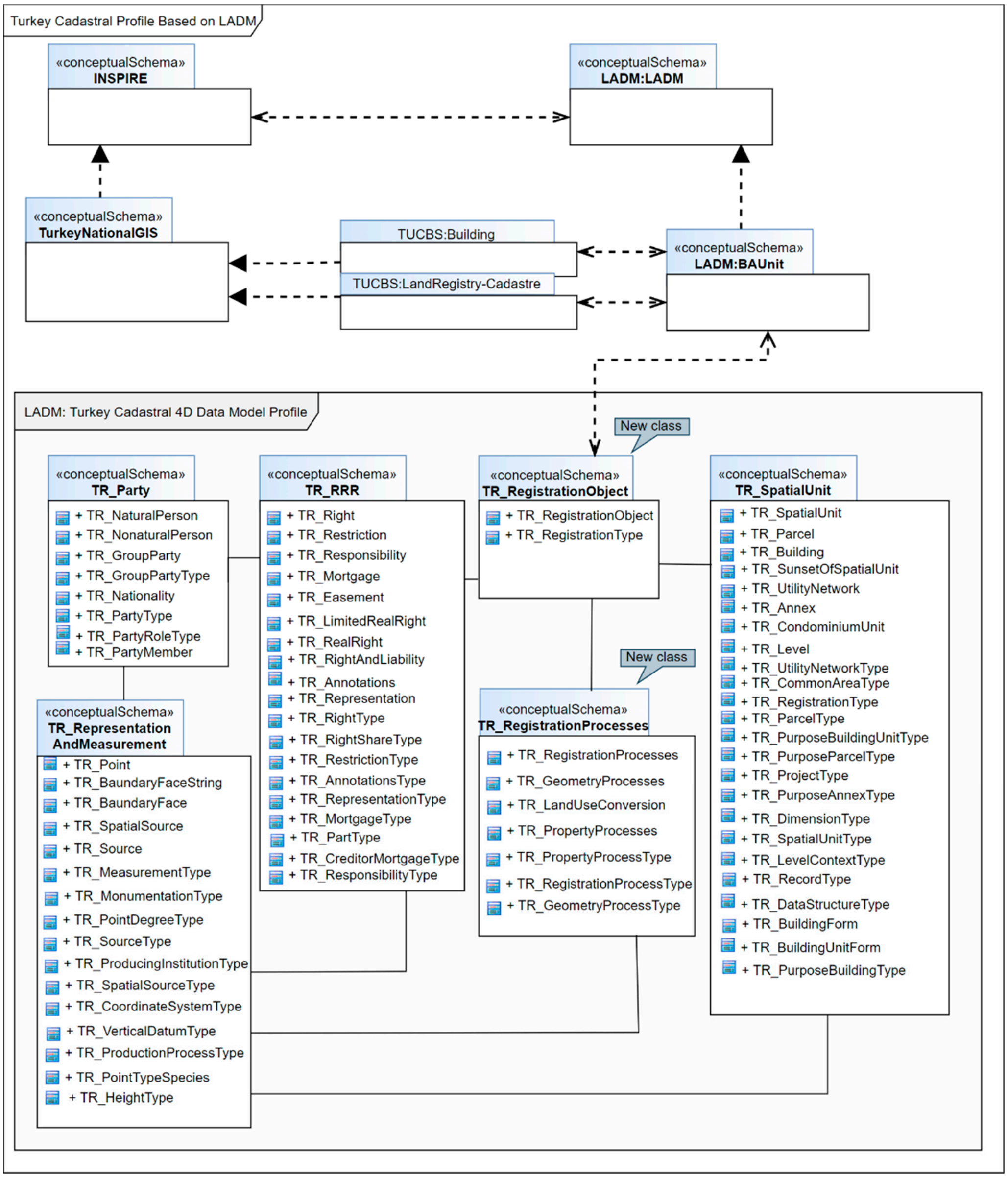

Figure 3. Shows the general framework for modelling the legal part of the proposed integrated model based on LADM.

The Registration process class is new in the LADM for the Turkish cadastral system. It was created in the Administrative package and associated with the VersionObject class. In this class, transactions are made without changing the owner information of a real estate, or spatial planning is represented. The attributes in this class are determined according to Civil Law, Land Law, Cadastre Law, and Zoning Law. The geometrical processes, such as subdivision, land amalgamation, and land subdivision, are explained in the GeometryProcessType CodeList. According to the 3194 Zoning law, the land subdivision is the division of land, so that construction can be done in a way that allows for all infrastructure services, including public service and facility areas; however, the subdivision divides the land under certain conditions regardless of whether or not they are infrastructure services. The real estate and the owner information can be provided within the data of RealEstateID and PersonalID. The new and old real estate numbers generated due to the geometric processes are maintained. Moreover, the time period of these applications is represented by RegisterDate and DeleteDate.

The new Registration objects class in the proposed model, based on LADM, differs from The BAUnit class, which involves the registration process for the party to become official, with regard to the title registration rights. Whereas the BAUnit class represents the real estate owned by an owner, the RegistrationObjects class represents each real estate registered to the land registry separately. In the Turkish cadastral system, real estate registered to the title may consist of an independent section and an annex such as a coal cellar or a warehouse located separately from the independent section; therefore, in the proposed model, the RegistrationObjects class is considered a superclass of the Spatial Unit class and a subclass of the BAUnit class. The SpatialUnit class, which has sub-classes, parcels, buildings, and independent sections, is the parent class, where all cadastral objects are represented and associated with the other classes. The building class has a composition relation type with the parcel class, which is obligatory for the cadastral system. Although a building is located on only one parcel, there may be more buildings on a parcel. A building can have one or more independent parts, which is considered a spatial unit (related to one building). The Annex is located outside the independent section, such as the cellar and water tanks. Moreover, it cannot be registered in the title alone without the independent section to which it is not related; therefore, the 0..* (0-lots) association is selected between the condominium and Annex. Since the technical infrastructure facilities (electricity, telephone, drinking water, sewerage, and natural gas facilities) are not registered in the current cadastral system in Turkey, this section has been left out of the cadastral data model based on LADM.

The surveying and representation subpackage, a subpackage of the model, is a package with the spatial objects. Moreover, the geometric status is represented in the transaction processes. The package represents boundary points, 2D and 3D boundaries, the title, and other resources. Attributes of the package classes have been created following the LADM ISO19152 standards. Point ID, PointName, Map, Height, Coordinate type, Corner coordinates, and RegisterDate attributes for points are defined in the class. Some elements define a point. One of these is the SpatialSource class. The spatial source class is the class in which elements that assist in establishing or measuring a point, or which provide any data flow related to the point, are represented. These elements may be singular or plural; therefore, the one-to-many association's type is determined between point and spatial source classes.

The VersionedObjects has modelled each class's time information, including the time it starts and ends, and is defined by the name of the begin-lifespan version and the end-lifespan version, respectively [33,42]. The temporal expressions for the model are arranged according to the Turkish cadastral system. Namely, the begin-lifespan version is the Registered date, and the end-lifespan version is "Deleted date".

3.3. Linked LADM and CityGML for 4D Cadastre in Turkey

This section describes the creation of Turkey's ADE 4D Cadastral Data Model by adding new classes and their attributes to the CityGML LandUse and AbstractBuilding feature classes. In the innovative ADE, five new feature classes, which are TR_CondominiumUnit, TR_Building, TR_Annex and TR_BuildingUsePart, have been specified as the AbstracBuilding class's subclasses. TR_Parcel is defined as a subclass of the LandUse class. Although CityGML does not explicitly represent parcels, the OGC specification states that the LandUse class represents parcels as 3D [38]. The parcel, which is defined as a subclass of the LandUse class, inherits all attributes and associations from both the CityObject and LADM via the PyshcalObjects class.

The CityGML AbstractBuilding can sufficiently describe buildings and their subclasses because it has many attributes and code lists related to buildings (such as the number of floors, roof types, year of construction and demolition, usage, and so on). Although the AbstractBuilding class provides many attributes that are also valid in the Turkish cadastral system, it has been extended with more specific attributes, such as building number, building usage permit date, building license approval date, and building value for the developed model.

The second new class is the CondominiumUnit according to the Turkish cadastral system. CityGML does not have a class that defines the legal parts of buildings while representing the structural parts; therefore, representation of the legal parts is provided by LADM classes. New classes (CondominiumUnits, BuildingUsePart, and Annex) are created in CityGML for the physical details corresponding to these legal classes (as shown in Figure 4). These classes inherit all attributes and associations from their superclass Building.

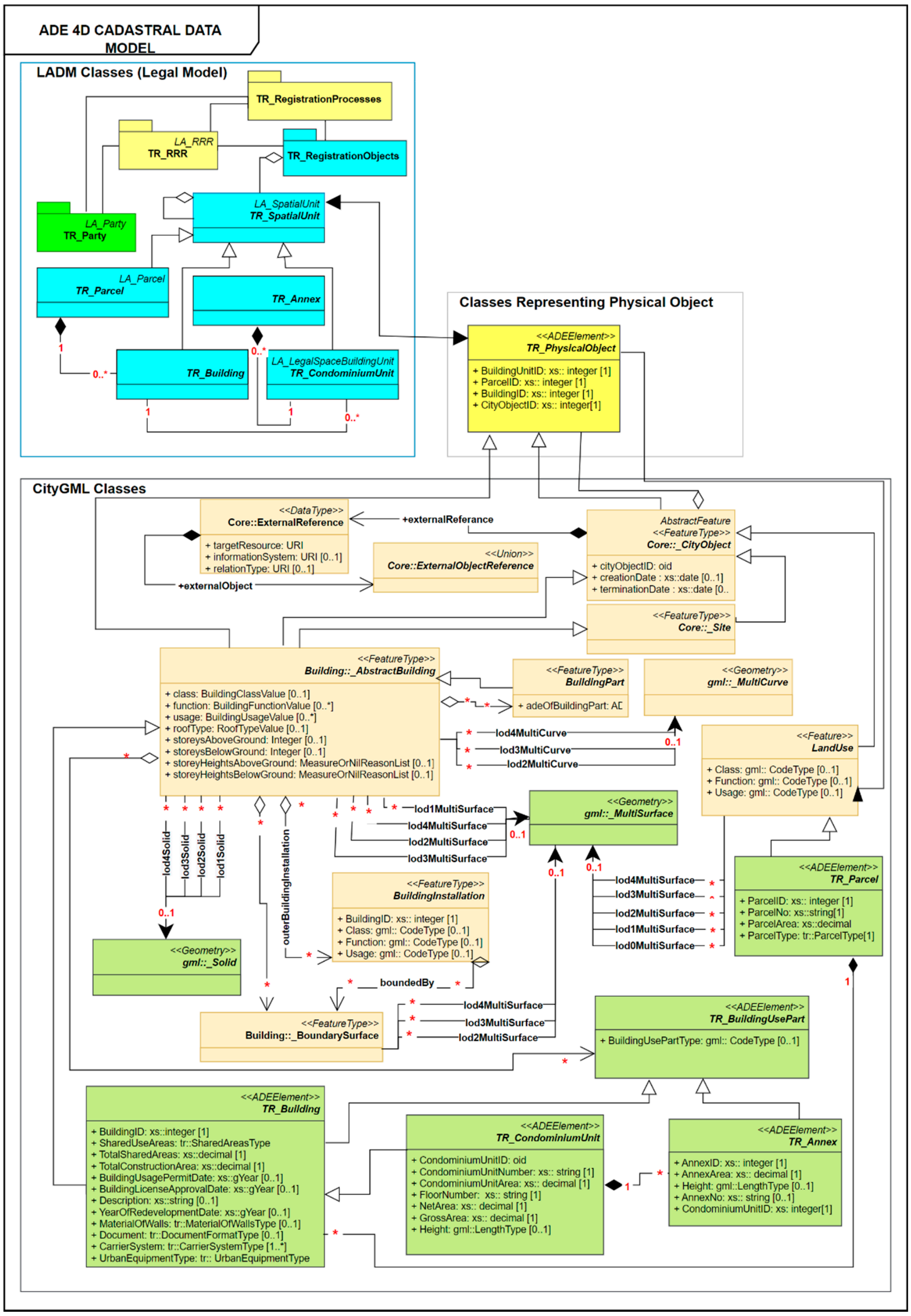

Figure 4. Shows the conceptual model for the new ADE 4D Cadastral Data Model.

The BuildingUsePart designates an association of many to many (*..*) between Building, CondominiumUnit and Annex classes. One or more parcels contain zero or more buildings that may have several condominium units. In the UML class diagram (Figure 4), the Parcel and Building composition association indicates several Parcel objects, including zero or more Building objects.

Figure 4 presents the innovative ADE Cadastral Data Model for Turkey's cadastral system. Thus, the conceptual model makes it easy to understand the associations between new classes and existing classes.

3.4. Integrated Models Developed Using International Standards for Cadastral Purposes

Integrated information models are designed for the combination of legal and physical objects, demonstrating that defining semantic information is possible at a representation level. Generally, there are two methods for creating integrated information models. The former is enriching physical information models with legal information. The latter defines an external association between legal and physical information models [3]. Various investigations integrate legal and physical information models for cadastral purposes. The integration of CityGML and LADM concepts has two methods. The first method is to design a profile of LADM for a particular country and then create a new ADE for the CityGML standard based on that profile. The second method involves designing an ADE for the CityGML standard according to the general legal concepts defined in LADM. Sun et al. [10] worked on modelling several requirements, considering legal and technical aspects for cadastral data building and city level. The authors developed a framework using these requirements for integrating 3D cadastre and 3D digital models. Another study links the buildings' legal and physical spaces for the Polish cadastre in [43]. Although LADM is used for legal spaces, CityGML is used for physical spaces. The implementation of LADM-based ADE of CityGML was tested, case studies were developed in LOD0 and LOD1 of CityGML, and other higher LODs (LOD2–4) were not considered in the implementation. The other study created an ADE to CityGML by using an extension for the cadastral/land administration [44]. The developed ADE also defined a new class, created cadastral building data, and allowed the identification of apartments and ownership rights for the apartments using a set of application-specific attributes for the CityGML AbstractBuilding class.

4. Creating Open-Source 4D Database and Visualization of New ADE 4D Cadastral Data Model

The 3D City Database (3DCityDB) was developed in collaboration with the private sector and university to manage, analyse, and query datasets of complex structures. It allows the automatic creation of large and complex CityGML data in the database, and the importing and exporting of data using the Import/Export tool. In addition, the 3D city model can be enriched by adding additional information to the relevant database tables [45]; however, the proposed integrated data model is designed to create new related classes, but not by adding additional information to CityGML (v 2.0) data tables. Therefore, creating the new model in 3DCityDB will not fully reflect the developed conceptual model. The conceptual model based on LADM is still a problem in terms of importing data into the database, as there are principles of normalization in the database design. The UML of the LADM diagram does not fully comply with these principles because LADM provides a conceptual representation. We discussed the LADM classes and transformed them into normalised tables. Sometimes an LADM class was represented by more than one database table.

Similarly, several LADM classes are shown in the same database table. PostgreSQL version 13, an open-source database management system for the 4D database, was used to test the proposed model. The conceptual data model, LADM, and CityGML classes were manually mapped to a relational database schema. Thus, the conceptual model will provide great convenience to users who need to interact directly with the tables in the database. The generated Python code transfers CityGML data to the designated database, and can be viewed on the relevant GitHub page (https://github.com/hicretgs/CityGmlParser, accessed on 12 March 2022). First, an empty database schema related to the ADE 4D Cadastre Data Model was created in the PostgreSQL/PostGIS Database. This establishes a connection between the database and the installer tool, which was created with a new SQL code. Secondly, all the data required in the ADE 4D Cadastre Data Models were transferred to the database, starting with the upper classes in the models. The loader tool does not provide alternatives to implement the generalization relationship, and the only option is to generate all classes with inherited properties automatically. CityGML data has been transferred to the relevant tables as a result of the generated code. Figure 5 shows the steps taken to import data from an integrated model into a 4D database, and to present the data in a 3D visualization platform such as CesiumJS.

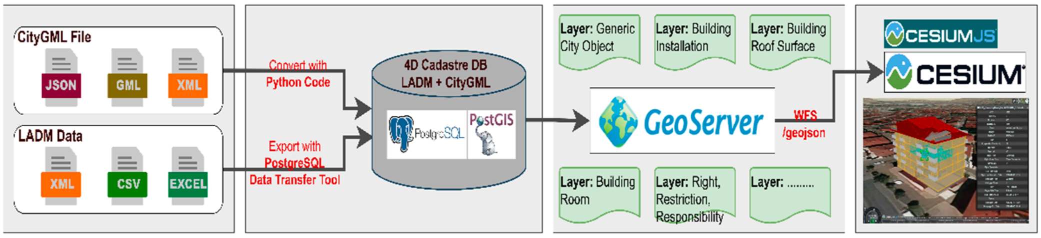

Figure 5. Workflow of processing steps to creating ADE 4D Cadastral Data Model and implementation.

4.1. Web Feature Service

Though the developed 4D database offers extensive functionality for reading and presenting the CityGML and LADM classes, it can only be implemented in a desktop environment. To overcome this limitation, ADE needs web-based access to 3D cadastral objects stored in the 4D cadastral database. The ADE 4D cadastral database uses a web service that implements the OGC Web Feature Service 2.0 (WFS 2.0) Interface Standard. GeoServer is open-source software based on Java. It allows users to access and work with geographic data from different environments. GeoServer can use vector (Oracle Spatial, ArcSDE, DB2, MySQL, PostGIS, Shapefiles, and Web Services) and raster (ArcGrid, GeoTiff, 51 Jpeg2000, ECW, MrSID) data as data sources [46]. It can also read formats such as KML, GML, GeoRSS, and GeoPDF, which are produced in standard protocols. GeoServer conforms to the WFS standard, allowing the sharing and editing of data to create maps. The data in the 4D database was converted to JSON (JavaScript Object Notation), a lightweight data-interchange format via GeoServer. JSON is a text format that is entirely language-independent and uses programming languages of C, C++, C#, Java, JavaScript, Perl, Python, and many others. These properties make JSON an ideal data-interchange language. JSON is a format used by many visualization platforms such as CesiumJS [45].

4.2. Visualization of the Cadastral Information with the Buildings in 4D Using CesiumJS

The CesiumJS is a JavaScript library for creating 3D globes and interactive maps in a web browser without a plugin. An OGC standard since 2019, it visualises and analyses 3D geospatial datasets on a high-precision WGS84 globe. The Cesium has a website and uses Sandcastle. As a result of Sandcastle, it helps test the codes used in the CesiumJS interface. The Cesium supports special data formats such as the Vector format (KML, GeoJSON, TopoJSON), 3D model (glTF models (graphic language Transmission Format), 3D Tiles, Terrain (Heightmap), and Imagery (WMS, ArcGIS, Google Earth, Open Street Map). Three-dimensional Tiles stream massive heterogeneous 3D geospatial datasets, including photogrammetry models, 3D buildings, CAD and BIM exterior and interiors, and point clouds. Three-dimensional models/formats can be converted to 3D Tiles. The JavaScript code should be used to show the Tilesets in the browser. A 3D Tiles structure is a component with spatial data structure, glTF, some styling, and metadata [45,46].

Our study developed a 4D database using the Turkish cadastral system's proposed integrated data model (CityGML and LADM). The time information available in the Turkish cadastral system could be applied both in the conceptual model and in the database. The conceptual model is fully represented in the database. After this stage, the data was converted into a vector format (GeoJSON) using GeoServer, and visualized on the Cesium platform so that the database could be queried interactively. In order to connect the GeoServer to the Cesium platform, a new code was written using the Cesium JavaScript API library. In addition, SQL queries were written to create layers in GeoServer. This process has been completed in order to display different information together in the information box for each independent section. Figure 6 shows a 3D representation of a building. Information about any independent section is available in the information box on the right. In addition, it is possible to query the time information concerning when transactions were made. Both title and mortgage information can be displayed in the selected independent section.

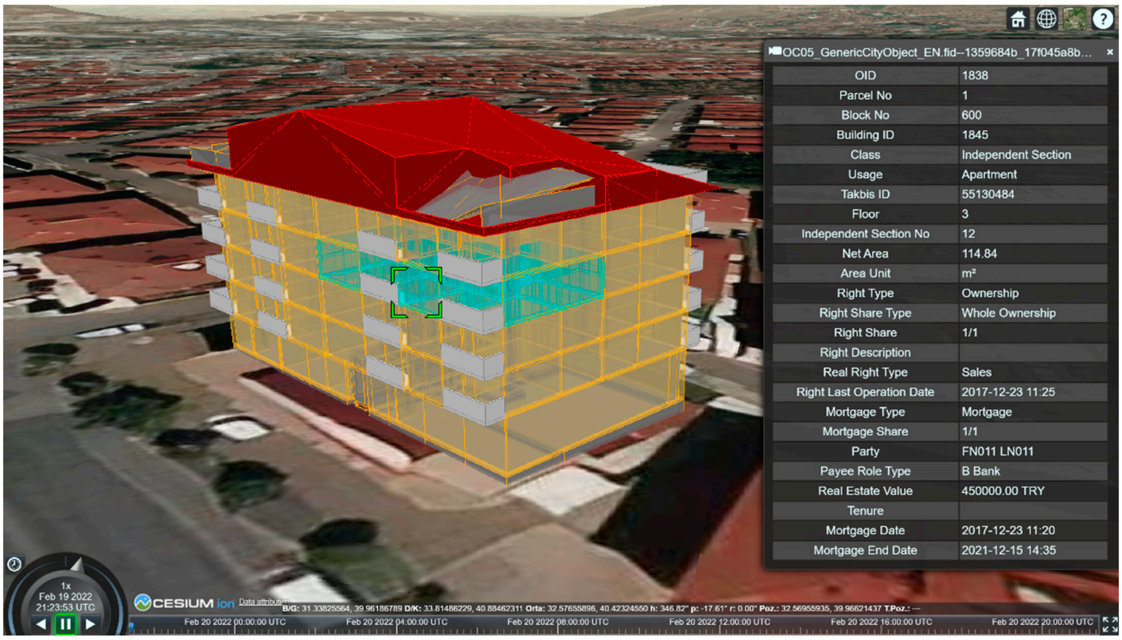

Figure 6. The 3D visualization of the created 3D Building is based on the Turkish cadastral system's ADE 4D Cadastral Data Model, and its time and cadastral information results.

5. Discussion and Conclusions

Legal interests and physical boundaries in Turkey are the cadastral system's primary elements. This study contributes by proposing a new ADE 4D Cadastral Data Model that can represent legal and physical objects together, enriching 3D cadastral studies with time information. The results are discussed below from legal and physical perspectives.

5.1. Legal Perspectives

The Turkish cadastral system, built on a 2D parcel and digital map, needs to be developed at an international level in order to transition to the 3D cadastral system. In addition, the processing steps required for the 3D conversion of the existing system and the 3D cadastral objects must be defined by laws and regulations. For the coordination of, and relationship between, all stakeholders involved in the cadastral system and the RRR, cadastral procedures should be defined using international standards so that all data and documents are suitable for integrating and visualizing the 3D cadastre. In order to overcome all these deficiencies, different integrated data models (LADM-LandInfra, CityGML-IFC, LADM-IndoorGML, LADM-CityGML) have been developed under country profiles. In this context, the widely accepted LADM standard has been providing a common approach for sharing and exchanging land administration data with other jurisdictions. This advantage is the basis for standard development in data storage, sharing and managing relations between relevant stakeholders in cadastral systems for many countries; however, despite all these features, there are limitations to the 3D physical representation of real estate. Therefore, to create a complete 3D cadastral system, it is necessary to represent cadastral data and their corresponding physical details with models at the conceptual level, and store and integrate them with geometrical visualization in 3D. This study uses the LADM to create 4D terminology and establish a common ontology for the modelling of legal data. A comparison and a common association has been established between the cadastral objects and their time attribute and LADM. It is discussed how the time information provided by the LADM Version Object class can be applied to the Turkish cadastral system. The new Registration Process class we have created for the event and state-based temporal inquiries allows for the historical information and temporal inquiries of real estate to be noted. Thus, the developed model provides a general framework for other countries, which studies their country profiles based on LADM.

5.2. Physical Perspectives

Although physical information models can represent the physical details of objects at different levels, they are insufficient to describe and manage their legal information. Physical objects represented in physical models such as CityGML, IndoorGML and IFC are not meaningful unless they contain legal information; therefore, for a meaningful 3D cadastre, an integrated data model has been used, which allows for adequate representation of cadastral objects both legally and physically. The Turkish cadastral system uses CityGML to model the physical interest corresponding to the legal interest. As CityGML is the most widely used data standard that gives sufficient detail compared with the current system in Turkey, each instance of 'Room', 'BuildingUsePart', 'BuildingInstallation', and 'IntBuildingInstallation' entities in CityGML could be considered as single parts of common property. These classes link to 'CityObject' directly, but direct inheritance is not always the correct solution for adopting potential entities for land administration purposes; therefore, the extension mechanisms should be used for defining the attributes of legal interest. Moreover, if the building parts share property rights, creating a specific and complete UML model is necessary to integrate with physical models (see Figure 4). The newly developed integrated LADM and CityGML model enables both visualization and standardization within the scope of the 3D cadastre.

This study proposes a general framework for how the time information can be applied in the model, which is created by integrating cadastral information with LADM on legal objects and CityGML on physical objects. The main requirements for creating a 4D cadastral model for Turkey are presented with legal and physical perspectives from existing cadastral objects. The study was tested using actual data in a case study. Thus, cadastral data modelling, and managing and serving stages, have been examined individually within the scope of the research and are similar to a handbook that has been created for different users. The difference between our study compared with other studies in this field is that all the processing steps (analysis, modelling, storage, data conversion and service, visualization) performed for 3D cadastre studies are explained, and open-source software was used within the scope of the application. Moreover, it is a problem for databases developed outside of 3DCityDB to transfer CityGML data to the database by matching with LADM due to the lack of an import/export tool. This deficiency has been eliminated by writing a SQL code that matches LADM and CityGML data classes, which transfers it to the database. The ADE model that was created, is designed to allow temporal queries; however, temporal queries were not seen, as the query panel is not created using the Cesium platform. Our previous study [20] has detailed information about the temporal queries made from the database for the same data model. The temporal expressions in the data model and the associations between the classes allow querying the data in specific periods. Since the data model developed in the study mentioned above was tested for temporal inquiries, it is thought that temporal attributes and associations are sufficient to represent the existing cadastral system with 4D; however, an additional panel must be created for temporal queries on the Cesium platform. For further studies, the creation of an inquiry panel in Cesium has been planned, in addition to testing the model for different scenarios. The contributions of our study to the literature are listed below.

- A case study was conducted for the Turkish cadastral system with time information which visualized the rights and restrictions of 3D spatial units. The legal model was created by examining the Turkish cadastral system and the existing laws (Civil Law, Land Law, Cadastre Law, Zoning Law, Condominium Ownership Act.), and was integrated into the widely used CityGML data model, which provides 3D representation. In addition, it has been investigated how the time information presented by the LADM VersionObjects class should be applied to the proposed integrated model. In the current study, we believe that we show how the data can be synchronized.
- The complete transfer of conceptual/logical UML models to physical DB environments is still a significant problem in the literature because database design has normalization principles. The UML of the LADM diagram does not fully comply with these principles because LADM offers a conceptual representation. We discussed the LADM classes and converted them into normalized tables. Sometimes, an LADM class was represented by more than one database table. Likewise, several LADM classes are shown in the same database table. Whether the database fully represents the developed model, different scenarios in the cadastral system were studied. A new code was written using Python to transfer CityGML data to the developed database. The GeoServer that allows the database to be presented interactively was used to transfer all data and its associations in the database to the visualization platform. PostGIS data was converted to Vector (JSON) format via GeoServer and presented on the Cesium platform.

The study's outcomes suggest that different stakeholders share and exchange cadastral information with a standard model to describe complex cadastral boundaries to develop an extensive 3D cadastre; therefore, this study argues that the proposed model will create a model framework for achieving this transformation and contribute to the model's applicability.

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