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Linking Land Administration Domain Model and BIM environment for 3D digital cadastre in multi-storey buildings

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ABSTRACT

3D digital cadastral systems intend to provide a fully-integrated 3D view of legal boundaries and rights, restrictions and responsibilities (RRR) in multi-storey properties, which is aligned with the physical reality. Our cognitive understanding of legal boundaries and RRR information is more communicable when we link it to our visual perception of the real world. However, there is a knowledge gap in logical relationships between legal and physical views as most of the existing approaches that integrate 3D legal and physical dimensions have been mainly proposed on a conceptual level. The main argument of this study is that the multi-dimensional nature of BIM provides the ability to extend this environment with concepts defined in Land Administration Domain Model (LADM) for the purpose of 3D digital cadastre in buildings. Therefore, this study investigated how an open BIM-based data model, known as Industry Foundation Classes (IFC), can be extended with LADM data elements to support integration of legal and physical views. This will create a linkage between LADM and BIM environment, which would subsequently provide a better cognitive understanding of legal spaces.

1. Introduction

To support more people living in closer proximity, urban environments are becoming densified with the establishment of multi-storey buildings. The growing dominance of these buildings is shifting cities towards higher degrees of physical and functional complexities, creating significant challenges in managing legal boundaries and rights, restrictions, and responsibilities (RRR) related to private, communal and public properties (van Oosterom, 2018). The problem is that current land and property subdivision practices rely on two dimensional (2D) drawings which usually represent fragmented projections of 3D reality of multi-storey buildings (Atazadeh et al., 2017a, 2016b; Olfat et al., 2019; Rajabifard et al., 2018b). Interpretation of these 2D drawings often requires significant expertise and experience to disambiguate the spatial location of legal boundaries and RRR information. Over the last decades, 3D digital cadastre has been introduced as a new paradigm to address land administration challenges in complex environments, fostering the engagement of a broader community of many important stakeholders involved in land and property related decision making (Stoter, 2004; van Oosterom, 2013; van Oosterom et al., 2020). 3D digital cadastre aims to provide a fully-integrated 3D view of legal boundaries and RRR information, which aligns with the physical reality (Pouliot et al., 2018). This integrated representation is more readable and congruous with our visual perception of the real world, which is overlaid with our cognitive imagination of legal boundaries and RRR information. Therefore, two categories of concepts underpin the realisation of 3D digital cadastre: legal and physical (Atazadeh et al., 2018a).

3D legal models have been developed separately from 3D models describing the physical dimensions of built environments. There have been significant research efforts towards integration of legal and physical aspects of built environments. However, the existing approaches that integrate 3D legal and physical dimensions have been mainly proposed on a conceptual level (Kalogianni et al., 2017; Rajabifard et al., 2018b).

In the land administration sector, Land Administration Domain Model (LADM) is an international standard that includes fundamental and jurisdiction-independent concepts required for modelling legal boundaries and RRR information (Lemmen et al., 2015; Paulsson and Paasch, 2015). LADM provides a common ontology to facilitate

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exchange of land and property information within a jurisdiction or among different jurisdictions (ISO19152, 2012). The conceptual essence of LADM provides the flexibility to implement this standard using a broad range of approaches predicated on jurisdiction profiles, each of which is unique in addressing specific requirements of a particular jurisdiction. The existing literature indicates that the viability of LADM for 3D digital cadastre was investigated in various jurisdictions around the world (Janečka et al., 2018). These jurisdictions include Brazil (Purificação et al., 2019), China (Ying et al., 2018; Yu et al., 2017; Zhuo et al., 2015), Czech (Janečka and Souček, 2017, 2016), Croatia (Mader et al., 2018, 2015; Vučić et al., 2017, 2013), Greece (Gkeli et al., 2018; Kalogianni, 2015; Kitsakis et al., 2018), Israel (Felus et al., 2014; van Oosterom, 2014), Korea (Kim et al., 2015; Lee et al., 2015), Serbia (Radulovic et al., 2018, 2017a, 2017b), Malaysia (Jamil et al., 2017; Rajabifard et al., 2018a; Zulkifli et al., 2015, 2014b, 2014a), the Netherlands (Stoter et al., 2013), Poland (Góźdź and van Oosterom, 2016), Russia (Vandysheva et al., 2011b, 2011a), Trinidad and Tobago (Griffith-Charles et al., 2016), and Turkey (Alkan and Polat, 2018; Aydinoglu and Bovkir, 2017; Polat and Alkan, 2018). Although LADM provides a comprehensive set of entities for modelling legal concepts, physical elements can be linked to LADM entities externally.

In the Architecture, Engineering and Construction (AEC) sector, Building Information Modelling (BIM) is a widely adopted 3D digital approach that enables the federated management of physical and functional characteristics of a building over its lifecycle (Isikdag, 2015; Wang et al., 2019). BIM provides a collaborative way of working among AEC stakeholders, unlocking the value of sharing information from the earliest conception till demolition of a building (Bryde et al., 2013). Interoperability in the BIM domain is achieved through an international standard, namely Industry Foundation Classes (IFC) (ISO16739, 2013). IFC provides a wide range of data elements to facilitate open data exchanges among various tools handling BIM data. From a 3D digital cadastre point of view, the focus of a BIM environment, and its open IFC standard, is on physical aspects of buildings. However, the multi-dimensional nature of BIM provides the ability to extend this environment with legal concepts for the purpose of 3D digital cadastre in buildings (Andrée et al., 2018; Atazadeh, 2017; Atazadeh et al., 2016b; Barton et al., 2010; Kalogianni et al., 2020; Oldfield et al., 2017).

This study aims to investigate how the IFC standard, which is the open BIM-based data model, can be extended with LADM data elements to support 3D digital cadastre in multi-storey buildings. The proposed approach will create a linkage between LADM and BIM environment, which would subsequently provide an international approach for integrating 3D legal and physical dimensions of buildings. With this in mind, the next section provides a comprehensive review of the current research that explored integration of LADM and various 3D physical models. In Section 3, a methodology for extending the IFC standard based on LADM concepts is developed, which is followed by implementing a BIM model enriched with LADM data elements in Section 4 to showcase feasibility of the proposed methodology. Section 5 includes a discussion about the benefits and challenges in linking LADM and BIM. The final section concludes the article with main findings and directions for future research. It should be noted that in this study the term 'property' is used in two meanings: 'ownership' as a land administration concept and 'attribute' as a data modelling term.

2. Review of current research

LADM is integrated with 3D physical models using two main approaches (Kalogianni et al., 2017):

- Defining external linkages between LADM and 3D physical models: This approach relies on attributes of some LADM entities that link legal spaces to physical objects.
- Encoding LADM concepts into 3D physical models: In this method, extension mechanisms allowed within a 3D physical model are harnessed to mesh the LADM concepts into the current data structure of the physical model.

In the following subsections, the current body of knowledge that contributes to the integration of LADM and major 3D physical models, including BIM, will be reviewed.

2.1. LADM and 3D geospatial models

A wide variety of 3D geospatial models have been developed for managing geometric, topologic and semantic aspects of built environments. The comprehensiveness of spatial and semantic information varies among 3D geospatial models. Some models focus on purely geometric representation of buildings, such as KML (Wilson et al., 2007) and VRML (ISO, 2004). However, other models provide the capability to manage the geometry, topology and semantics of buildings in an integrated environment (Zlatanova et al., 2012). Examples are CityGML, IndoorGML and LandInfra standards. Here, we will focus on the connection of LADM with these 3D standards.

2.1.1. CityGML

CityGML is a well-known standard in the geospatial domain for enabling interoperable exchange of 3D urban information models (Groger et al., 2012; Gröger and Plümer, 2012). The core model of CityGML can be extended with additional attributes and object types to allow the representation, management and analysis of 3D urban models for a wide range of applications (Biljecki et al., 2018). Relevant to this study, extending CityGML with legal information will enable the capability to represent legal boundaries and RRR spaces in the context of a 3D urban information model.

As suggested in (Rönsdorff et al., 2014), there are two methods for linking LADM and CityGML standards using the Application Domain Extension (ADE) mechanism. The first method relies on connecting LADM and CityGML at a general level, while the second approach considers the land administration specifics of a particular jurisdiction when integrating LADM and CityGML.

The general approach acquires the suitable entities from LADM and adds them into the proposed ADE for CityGML. In the ADE proposed by (Rönsdorff et al., 2014), basic administrative units (LA_BAUnit) are encoded using the instantiable 'Parcel' class. This class is externally linked to the 'LA_RRR' entity to define the legal status of the Parcel. The concept of 'LA_SpatialUnit' is mapped as the 'LegalSpace' class which is associated to geometric representations in level of detail-LoD0 and LoD1. A geometric representation in LoD0 is used to define surface-based spatial units, such as land parcels, while the LoD1 representation provides the ability to map those spatial units with a volumetric extent, such as apartment units.

Jurisdiction-specific profiles that integrate LADM and CityGML standards have been proposed in some countries including Russia, Poland, and China. In the Russian Federation, 3D legal objects are typically related to physical objects such as buildings, tunnels, and pipelines. The integration of LADM and CityGML for this jurisdiction was investigated by Vandysheva et al. (2011b). In this LADM-CityGML data model, the legal objects were modelled via defining subclasses for 'LA_SpatialUnit'. Only the semantic connection between legal objects for apartment units (RF_LegalSpaceBuildingUnit) and their physical counterparts (BuildingPart in CityGML) was defined in the jurisdiction profile of LADM-CityGML for Russia. Another study was conducted by Gózdz et al. (2014) who explored the feasibility of CityGML and LADM integration from a perspective of the Polish jurisdiction. There are three types of legal objects recorded in the Polish jurisdiction: parcels, buildings and apartments. The defined legal objects are semantically related to their physical counterparts by defining association relationships between them and '_AbstractBuilding' class in the CityGML. In addition, two new classes are defined in the CityGML schema: PL_Building (subclass of Building) and PL_BuildingPart (subclass of

BuildingPart). These classes model physical information that is specifically used in the Polish 3D cadastre. Li et al. (2016) proposed a new ADE for incorporating LADM concepts into the CityGML schema based on jurisdictional settings and legislative framework of China. The proposed ADE provides a precise description of the ownership structure of condominium units, reflecting the logical interdependencies between legal objects and relevant physical elements.

The above-reviewed investigations have attempted to link physical information, acquired from CityGML, and legal information, acquired from LADM, by considering specifics of their jurisdiction. These efforts led to the consideration of land administration as one major domain of application for CityGML. As a result, the CityGML version 3.0 is expected to be more interoperable with the LADM standard (Kutzner and Kolbe, 2018). For instance, logical spaces (such as legal spaces) will be distinguished from physical spaces in the new version of the CityGML standard.

2.1.2. IndoorGML

The IndoorGML standard provides a 3D geospatial model in support of indoor navigation systems (Lee et al., 2014). In contrast to CityGML and IFC, which describe the physical reality in general, this standard is application-oriented data model that is used for navigating indoor environments. (Zlatanova et al., 2016a) argued that bridging LADM and IndoorGML would provide an integrated approach to link physical spaces and RRR information for a number of use cases related to indoor navigation. For instance, indoor environments, such as airports, metro stations, and shopping centres, include areas with different restrictions and rights (Zlatanova et al., 2016b). While some areas can be navigated by the public, others are restricted to the navigation by specific users such as security, maintenance and administration staff. To demonstrate these use cases, Alattas et al. (2017) investigated the combination of LADM and IndoorGML for the purpose of indoor accessibility predicated on RRR information. This helps users to avoid inaccessible spaces based on the RRR information entitled to them. Implementation of the combined LADM-IndoorGML model for two university buildings showcased the viability of the proposed approach for supporting an RRR-based indoor navigation in a real-world context.

More recently, the issues and challenges in converting LADM-IndoorGML conceptual model to a technical implementation were investigated. The transformation problems occurred mainly in correct handling of primary and foreign keys, associations, cardinality of multiplicity, spatial and non-spatial data types, spatial data indexing, constraints, and inheritance (Alattas et al., 2018a). Addressing these issues led to the development of a database for the LADM-IndoorGML model, enabling queries for retrieving accessible and inaccessible indoor spaces based on RRR information (Alattas et al., 2018b). The LADM-IndoorGML model was also utilized for evacuation purposes in complex buildings (Alattas et al., 2018c). Linking LADM and IndoorGML standards is still on a conceptual level (Tekavec and Lisec, 2020), which is an ongoing investigation that will lay the foundation of future indoor navigation systems integrated with RRR information.

2.1.3. LandInfra/InfraGML

The Land and Infrastructure (LandInfra) conceptual standard has been recently developed to support digital management of land and infrastructure facilities such as roads, railways, tunnels, surveys, alignments, land division and condominium units (Scarponcini et al., 2016). LandInfra concepts were implemented using a GML-based encoding called InfraGML. The legal concepts defined in LandInfra (and their implemented equivalents in InfraGML) are in line with a subset of the LADM standard. LandInfra does not consider the specific classes of party package as defined in LADM. RRR information is modelled by the 'InterestInLand' class in LandInfra. In addition, the geometric modelling of spatial units is independent from the legal ownership of these units. Therefore, LandInfra is more focused on infrastructure and cadastral surveying with less emphasis on the legal and administrative aspects of land development. Stubkjær et al. (2018) highlighted the need for harmonising LandInfra and LADM standards in the land administration domain. More specifically, cross-standard management of code lists was proposed to facilitate semantic harmonisation of concepts between LADM and LandInfra, resulting in mitigation of interoperability issues in the land administration domain. Compared to LADM, LandInfra includes more granular code lists to support semantic management of condominium units (Çağdaş et al., 2018). These code lists include condominiumMainPart, condominiumAccessoryPart, jointAccessFacility, and jointOtherFacility. However, in LADM, there is only the 'LA_BuildingUnitType' code list with generic 'shared' and 'individual' values (Çağdaş et al., 2018).

2.2. LADM and BIM

BIM-driven land administration is a new area of research with promising solutions for the 3D digital cadastre (Atazadeh et al., 2018b). There are investigations that looked at the enrichment of BIM, specifically the IFC standard, with legal information for different jurisdictions around the world, such as Victoria (Atazadeh et al., 2017b, 2016a), Netherlands (Stoter et al., 2017) and Sweden (Andrée et al., 2018; El-Mekawy et al., 2014; Sun and Paulsson, 2020). These investigations considered the specific requirements of each jurisdiction to integrate legal and physical dimensions in the 3D BIM environment. They did not adopt the LADM standard as a basis for managing legal information in the BIM environment. A more relevant study was conducted by Atazadeh et al. (2018a) who considered two conceptual approaches for connecting LADM and IFC standards to realise an open standard-based environment for integrating 3D legal and physical data: extending the IFC standard with LADM data elements or further development of LADM with IFC-based physical elements. The latter approach would not be a feasible approach due to some reasons. First, LADM is a jurisdiction independent model and adding physical elements will make the standard complex since the use of physical elements to manage and communicate legal interests differs from one jurisdiction to another. Another reason is that the IFC standard includes hundreds of entities to model the physical dimensions of buildings that makes it challenging to choose the important physical elements to be integrated into the LADM standard. Therefore, the former option which is extending IFC standard with LADM concepts can be a viable solution to integrate legal and physical information in 3D. The mapping of LADM concepts into the IFC standard was also highlighted by Oldfield et al. (2017). The studies conducted by Atazadeh et al. (2018a) and Oldfield et al. (2017) are limited in terms of practicality and feasibility. In a recent study by Tekavec et al. (2020), a 3D cadastral data model for buildings was developed and the conceptual interlinkage of this data model with LADM was demonstrated. In addition, integrations of the developed data model with IFC, CityGML and IndoorGML standards have been investigated.

Overall, there are three approaches for linking LADM with 3D physical models: 1) extending LADM 2) extending the corresponding 3D physical model 3) providing a mapping between LADM and 3D physical models. Among these approaches, the second approach is found to be feasible in the context of linking LADM with IFC standard. Therefore, in the subsequent sections, we will extend BIM environment with LADM concepts for the purpose of 3D digital cadastre in multi-storey buildings and demonstrate the feasibility of this extension by implementing it for a real-world multi-storey building.

3. Proposed approach for linking LADM and IFC

The proposed approach is in line with the logic of extension methods adopted in the IFC standard. The recommended methods for extending the IFC standard are predicated on using the concepts of 'property sets' and 'user defined' values, which do not disrupt the IFC data structure significantly. LADM includes three packages, namely party, administrative and spatial units, and the 'Surveying and Representation' sub-package. In the subsequent sections, we will show how each package will be mapped into the IFC standard. This mapping will consider similarities between LADM and IFC to avoid duplicating data elements. Our reference for the legal view considered in this study is based on the concepts (LA_SpatialUnit, LA_BoundaryFace, LA_BAUnit, etc) defined in the LADM standard. The main idea is to develop an approach based on the IFC standard to technically encode the LADM (legal concepts) into the BIM environment.

3.1. Parties in IFC

Parties (LA_Party) can be mapped using the 'IfcActor' entity. In addition, various entities defined in the "IfcActorResource" subschema in the resource layer of IFC are relevant for mapping parties. These entities are (see Fig. 1):

- IfcActorRole: This entity defines the role of an actor. The "role" attribute of "LA_Party" can be mapped using the 'Role' or 'UserDefinedRole' attributes of "IfcActorRole". Enumeration values of the "LA_PartyRoleType" can be included in the "IfcRoleEnum" enumeration. Alternatively, the "UserDefinedRole" attribute can include any value from the "LA_PartyRoleType" code list.
- IfcOrganization: This can be used for modelling organizations and non-natural persons as a specific type of parties defined in LADM.
- IfcPerson: Natural persons defined in the "LA_PartyType" code list can be modelled by the "IfcPerson" entity.
- IfcPersonAndOrganization: This entity can be used for modelling those parties acting on behalf of an organisation. For instance, an owners corporation manager can act on behalf of the owners corporation.

"IfcGroup" is an appropriate entity for grouping parties (LA_GroupParty). This can be achieved by defining the "IfcRelAssignsToGroup" objectified relationship between instances of "IfcActor" and "IfcGroup" entities. The assignment of parties to spatial units or administrative sources can be achieved through "IfcRelAssignsToActor" relationship between "IfcActor" and the relevant entity (all subclasses of IfcObjectDefinition). For instance, we can define the assignment between "IfcActor" and "IfcSpatialZone" entities to assign an owner to their RRR.

Attributes of "LA_Party", except the "role" attribute which is defined via IfcRoleEnum, can be mapped using a new property set (Pset_LA_Party) assigned to "IfcActor" entity. For group parties, the attributes of "LA_GroupParty" are assigned as another property set (Pset_LA_GroupParty) to the "IfcGroup" entity. These property sets are presented in Table 1.

3.2. Spatial Units Package in IFC

Spatial units are defined in LADM to represent a single area or

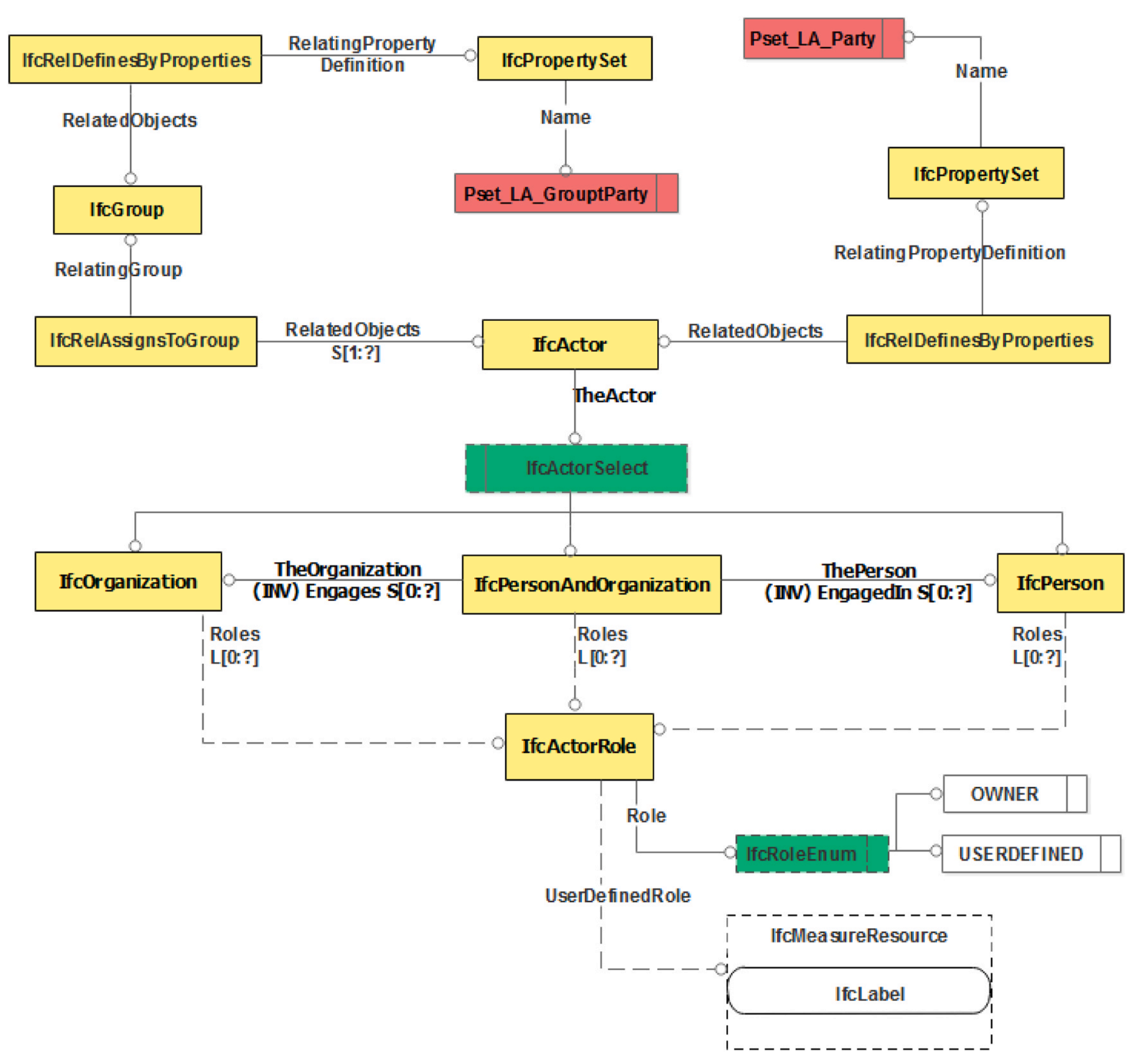

Fig. 1. Modelling parties in the IFC standard.

Table 1
Property sets for party and group party.

	Attribute name	Property type	Data type
Pset_LA_Party	extPID	IfcPropertySingleValue	IfcIdentifier
	Name	IfcPropertySingleValue	IfcLable
	pID	IfcPropertySingleValue	IfcIdentifier
	Type	IfcPropertyEnumeratedValue	IfcLable
Pset_LA_GroupParty	groupID	IfcPropertySingleValue	IfcIdentifier
	Type	IfcPropertyEnumeratedValue	IfcLable

multiple areas of land and water, as well as single volume or multiple volumes of spaces. In the context of 3D cadastre, 2.5D land parcels and 3D legal spaces are common forms of spatial units. More specifically, LADM defines two special types of 3D legal spaces: building unit (LA_LegalSpaceBuildingUnit) and utility network (LA_LegalSpaceUtilityNetwork). A building unit defines a 3D legal space associated with a building or a building part. A utility network is a 3D legal space for the entire topology of a utility. The legal extent of building units and utility networks is not essentially the same as their physical extent.

We identified the suitable IFC entities for mapping different spatial units.

- 2.5D land parcels: IfcSite is appropriate for mapping spatial units that represent 2.5D land parcels.
- Building units: In IFC, indoor spaces are modelled by IfcSpace while outdoor spaces are defined by IfcExternalSpatialElement. Therefore, both IfcSpace and IfcExternalSpatialElement are found suitable for mapping building units. For example, an apartment unit which is enclosed in an indoor space can be defined by IfcSpace, whereas an airspace right can be mapped by IfcExternalSpatialElement.
- Utility networks: Similar to building units, IfcSpace and IfcExternalSpatialUnit entities are suitable for mapping the legal extent of utility networks. The legal space associated with an individual part of a utility network can be modelled using IfcSpace and IfcExternalSpatialElement entities. However, utility networks are typically complex and include many interwinted elements. To manage the entire spatial structure of the legal extent of utility networks, it is suggested to use IfcSpatialZone entity since this enity uses IfcRelReferencedInSpatialStructure relationship to interlink IfcSpatialElement subclasses including IfcSpace and IfcExternalSpatialElement, and IfcElement subclasses including IfcDistributionElement. The important IFC entities considered for mapping the complex legal extent of utility networks are shown in Fig. 2.

Attributes of spatial units are defined as a property set named "Pset_LA_SpatialUnit" in IFC schema (see Table 2). These attributes can be applied to the IFC entities that can be used for modelling spatial units, such as IfcSite, IfcSpace and IfcExternalSpatialElement.

The topological consistency of the spatial units/land parcels can be considered at two levels: internal and external. The internal topological consistency provides a mechanism to ensure that an individual spatial unit/land parcel is valid while the external topological consistency uses adjacency relationships between spatial units/land parcels to avoid gaps

Table 2
Attributes of spatial units proposed as a property set in IFC.

Property set name	Pset_LA_SpatialUnit	
Attribute name	Property type	Data type
Area	IfcPropertySingleValue	IfcAreaMeasure
Dimension	IfcPropertyEnumeratedValue	IfcLable
extAdressID	IfcPropertySingleValue	IfcIdentifier
lable	IfcPropertyEnumeratedValue	IfcLable
referencePoint	IfcPropertySingleValue	IfcCartesionPoint
suID	IfcPropertySingleValue	IfcIdentifier
surfaceRelation	IfcPropertyEnumeratedValue	IfcLable
Volume	IfcPropertySingleValue	IfcSolidMeasure

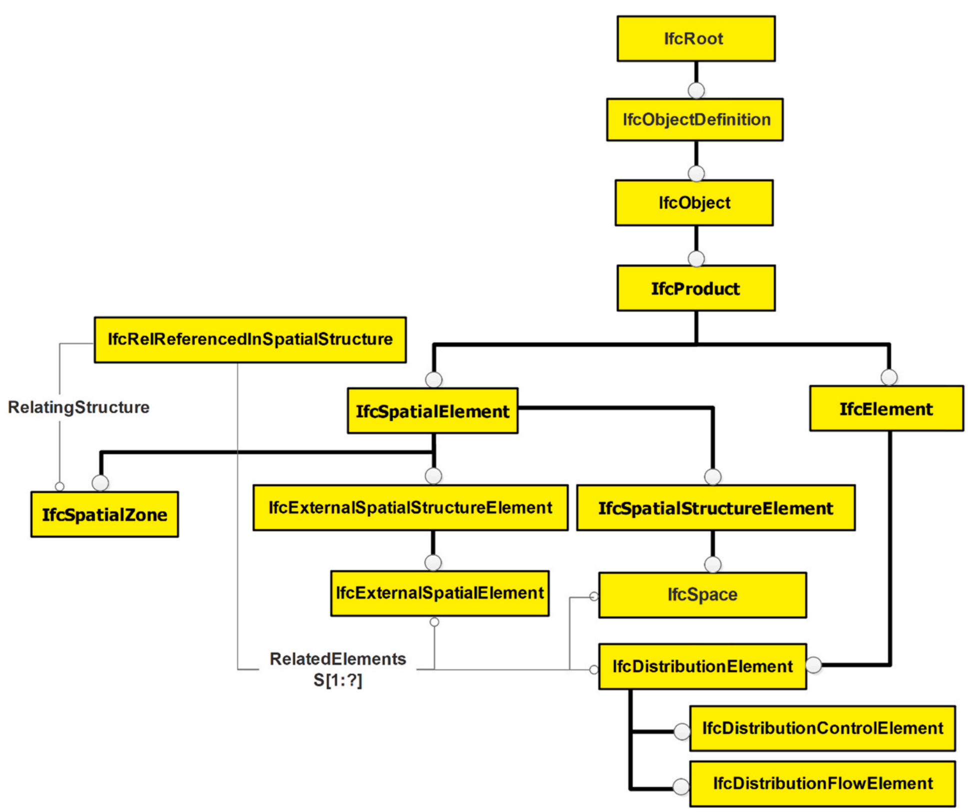

Fig. 2. Important IFC entities used for managing legal complexity of utility networks.

and overlaps. Spatial units (IfcSpace) are geometrically defined by boundary representation (B-rep) solids in IFC. Although B-rep does itself guarantee the topological integrity of spatial units, a strong aspect of this representation is to provide the ability to specify the"inside", "outside" and "on" regions of the spatial unit (Knoth et al., 2020). This ability would facilitate the internal and external topological checks for spatial units. For modelling land parcels, survey points geometric representation should be used in the IFC standard. The survey point representation of IfcSite is defined using a set of survey points and polylines. There is a restriction that the polylines must connect the survey points (BuildingSMART, 2013). This ensures the geometric closure of the land parcels (IfcSite), which would make it easier to perform internal and external topological checks on land parcels.

Other important concepts in the Spatial Unit package are level (LA_Level) and spatial unit group (LA_SpatialUnitGroup). A level is a set of spatial units with similar geometric, topological and thematic aspects. A spatial unit group is just a collection of spatial units. Similarly, in IFC, IfcZone entity is used for grouping a set of IfcSpace objects and IfcSpatialZone is composed of a set of spatial objects (subclasses of IfcSpatialElement) and physical elements (subclasses of IfcElement). Therefore, a group or level of spatial units can be handled using these entities.

3.3. Surveying and Representation sub package in IFC

The Surveying and Representation sub package in LADM includes basic concepts for modelling the bounding elements for spatial units. These include points (LA_Point), boundary face strings (LA_BoundaryFaceString) and boundary faces (LA_BoundaryFace). These concepts are similarly modelled in the IFC standard. IFC provides a wide variety of entities for representing lines and surfaces. Here, we will identify which ones are suitable to support LADM concepts.

For 2.5D land parcels, we mentioned that the IfcSite entity is suitable. The bounding limits of IfcSite are defined by 'survey points' geometric representation. This representation is provided by a set of survey points and optional break lines. Therefore, if a spatial unit is 2.5D land parcel, the concept of LA_Point can be modelled using the IfcCartesianPoint entity. Fig. 3 shows that IfcSite refers to IfcGeometricCurveSet entity. For mapping 2.5D land parcels, this entity provides the shape representation using a set of cartesian points (IfcCartesianPoint) and polylines (IfcPolyline) only.

In the IFC standard, various geometric and topological representations are considered for modelling boundary lines and surfaces. In addition, semantic information about boundaries (e.g. interior wall boundary) can be obtained in the IFC standard.

Boundary face strings are used to define the boundary between 2.5D land parcels. "IfcConnectionCurveGeometry" entity can be used to model the boundary face strings in IFC. There are two choices for defining the line boundary, namely a bounded curve (IfcBoundedCurve) or an edge with an associated curve (IfcEdgeCurve) via "IfcCurveOrEdgeCurve" selection data type. In this study, we proposed that "IfcEdgeCurve" should be chosen since it includes both topology and geometry of the line boundary (see Fig. 4). The current IFC standard does not specify the geometric connection between two instances of IfcSite. However, it is possible to define a line-based geometric connection between two land parcels using the IfcEdgeCurve entity.

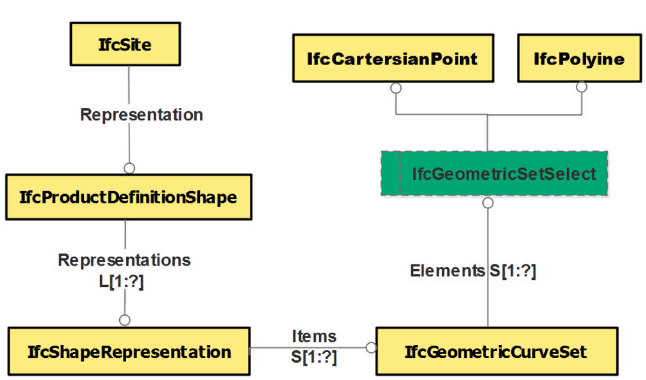

Fig. 3. Modelling points and boundaries face strings for 2.5D land parcels in IFC standard.

For modelling 3D legal spaces, we suggest "IfcRelSpaceBoundary" for modelling boundaries of 3D space since it includes the topological or geometric representation of the boundary through its "ConnectionGeometry" attribute which is associated to "IfcConnectionSurfaceGeometry". There are two options for defining the surface boundary, namely a surface (IfcSurface) or a face with an associated surface (IfcFaceSurface) via "IfcSurfaceOrFaceSurface" selection data type. In this study, we proposed that "IfcFaceSurface" should be chosen since it includes both topology and geometry of the surface boundary (see Fig. 4).

In summary, subclasses of IfcSpatialElement are suggested as suitable classes for modelling legal components. These subclasses are IfcSpatialZone, IfcSpace, IfcSite, and IfcExternalSpatialElement. The physical components in IFC are defined as subclasses of 'IfcElement' class. These subclasses include IfcBuildingElement (and its subclasses including IfcWall, IfcDoor, IfcWindow, IfcSlab), IfcDistributionElement, IfcGeographicElement, and IfcCivilElement. Fig. 5 shows different sections of the IFC standard, in which the legal and physical components are highlighted.

3.4. Administrative Package in IFC

There are three main concepts in administrative package: basic administrative units, RRR information, and administrative sources. There is no equivalent IFC entity for modelling basic administrative units (LA_BAUnit). Since the "LA_BAUnit" class typically refers to multiple spatial units, we define attributes of this class as a property set (Pset_LA_BAUnit) which can be applied to "IfcSpatialZone" and "IfcZone" entities (see Table 3). For modelling RRR information, LADM includes "LA_RRR" class and its subclasses "LA_Right", "LA_Restriction", and "LA_Responsibility" and "LA_Mortgage". There are also no equivalent IFC entities for these classes. One way of modelling RRR information in the IFC standard can be based on proposing the attributes of these classes as property sets assigned to IfcSpatialZone and IfcZone entities. To keep the relationship between basic administrative units and RRR information, zoning structures can be used in IFC. In other words, a basic administrative unit is defined using either IfcZone or IfcSpatialZone and then it is assigned to another IfcZone which defines a specific RRR information (e.g. ownership right).

Administrative sources (LA_AdministrativeSource) provide an administrative description or document that includes the involved parties, the created RRR information and the affected basic administrative units. The relevant IFC entities for modelling administrative sources are "IfcDocumentReference" and "IfcDocumentInformation" (see Fig. 6). The "IfcDocumentReference" entity provides a reference to the location of an administrative document via the "Location" attribute. "IfcDocumentInformation" provides more metadata about documents exchanged throughout the building lifecycle. In addition to the location of the document, this entity provides other metadata elements such as purpose, scope, intended use, document owner, editor, and so on. The referenced administrative documents are not contained within an IFC file; however, "IfcDocumentInformation" and "IfcDocumentReference" provide the ability to access them externally.

Documents can be related to other IFC entities via "IfcRelAssociatesDocument" relationship entity. For instance, this relationship can be used to associate a basic administrative unit (defined by IfcSpatialZone) to its administrative source (defined by IfcDocumentInformation). Another example could be associating a party (defined by IfcActor) to the relevant administrative source (defined by IfcDocumentReference).

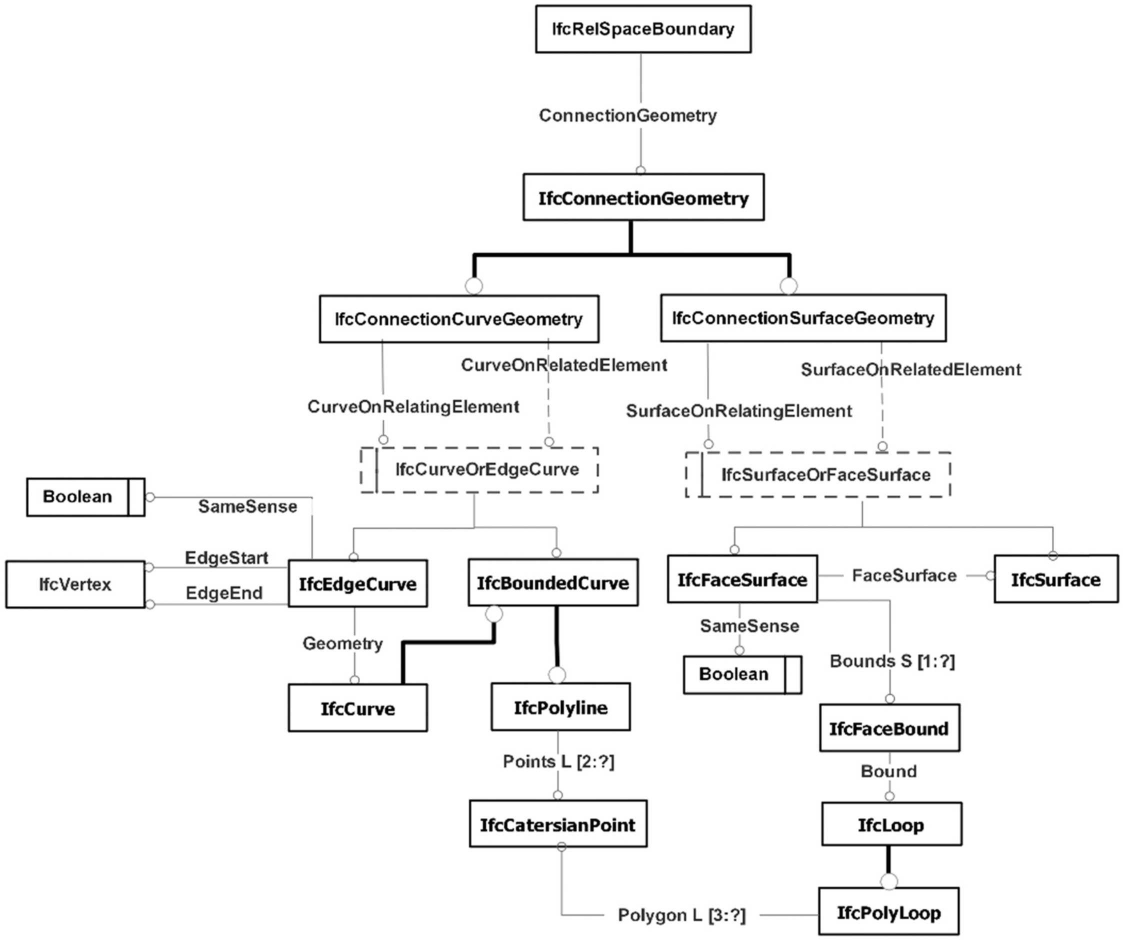

Fig. 4. Modelling boundary face and boundary face string for 3D legal spaces in the IFC standard.

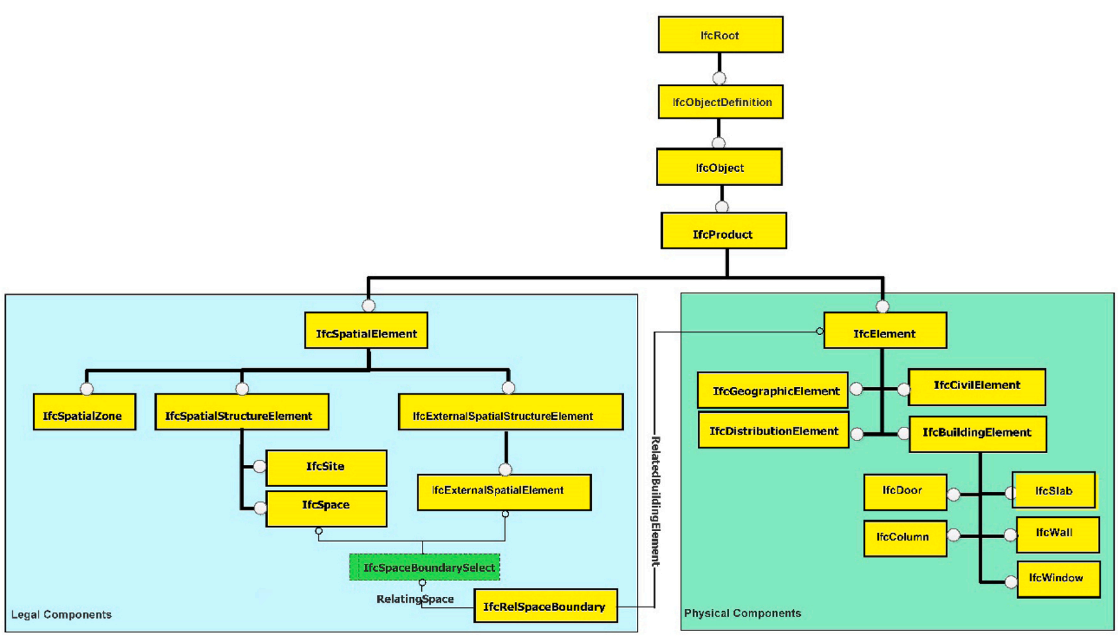

Fig. 5. Different sections of the IFC standard used for modelling legal and physical components.

4. Implementation

To demonstrate and validate the suggested approach for linking LADM and IFC standard, we implemented a prototype BIM model for an urban development comprising multi-storey buildings. The prototype model was constructed in Autodesk Revit. First, the physical model of

Table 3
Property sets for basic administrative units and RRR information.

	Attribute name	Property type	Data type
Pset_LA_BAUnit	Name	IfcPropertySingleValue	IfcLable
	Type	IfcPropertyEnumeratedValue	IfcLable
	uID	IfcPropertySingleValue	IfcIdentifier
Pset_LA_RRR	Description	IfcPropertySingleValue	IfcText
	rID	IfcPropertySingleValue	IfcIdentifier
	Share	IfcPropertySingleValue	IfcReal
	shareCheck	IfcPropertySingleValue	IfcBoolean
	timeSpec	IfcPropertySingleValue	IfcText
Pset_LA_Right	Type	IfcPropertyEnumeratedValue	IfcLable
Pset_LA_Restriction	partyRequired	IfcPropertySingleValue	IfcBoolean
	Type	IfcPropertyEnumeratedValue	IfcLable
Pset_LA_Responsibility	Type	IfcPropertyEnumeratedValue	IfcLable

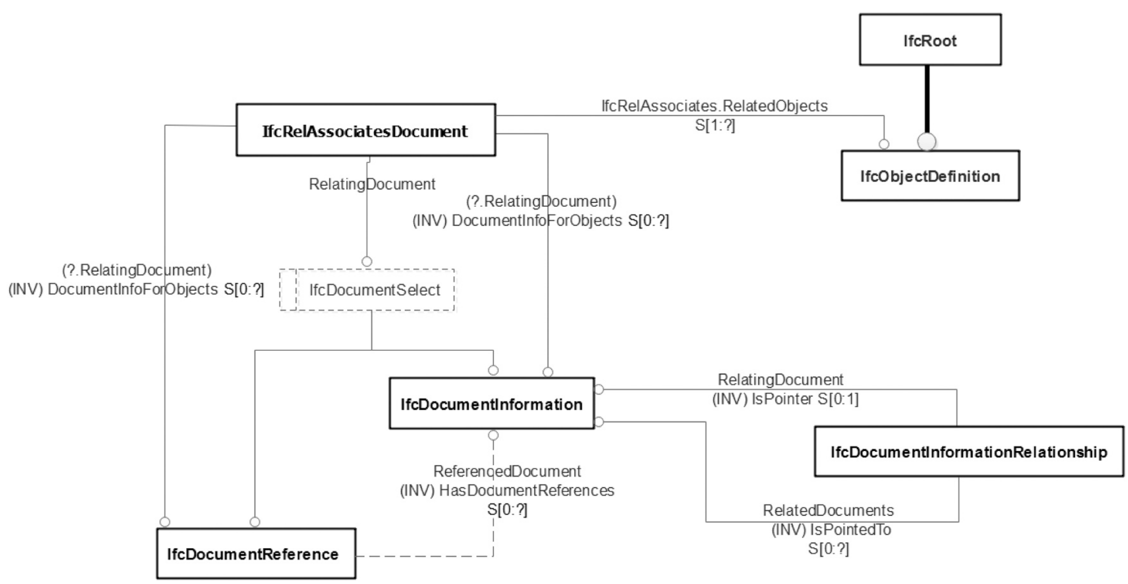

Fig. 6. Referencing administrative sources in the IFC standard.

the development was created. In the next step, legal boundaries defining the spatial units were delineated in the BIM model, which is followed by creating spatial units, namely 3D legal spaces and 2.5D land parcels. After defining spatial units, we defined basic administrative units for various ownership rights within the development. We used the custom IFC exporter in Revit to convert the BIM model to the IFC format. Property sets were assigned to the relevant IFC entities to define attributes for basic administrative units and RRR information. Parties were also assigned, e.g. owners, to the basic administrative units. Finally, administrative sources, such as title documents, were referenced in the IFC file. The following series of figures provide some examples of important LADM concepts implemented in the prototype BIM model. Fig. 7 shows a typical example of spatial unit created in multi-storey buildings, which shows volumetric ownership space for a building unit. In addition, the attributes of this spatial unit are represented in the prototype model based on the defined Pset_LA_SpatialUnit property set. Other examples of spatial units are the land parcel of the building before its subdivision (see Fig. 8a) and airspace rights on top of a multi-storey building (see Fig. 8b).

It is also possible to model basic administrative units using zone

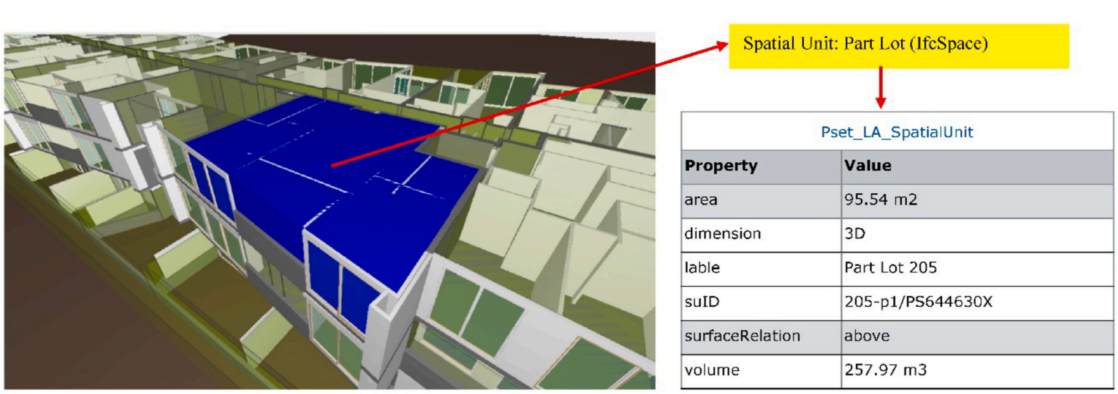

Fig. 7. A typical spatial unit (building unit) modelled in the BIM environment.

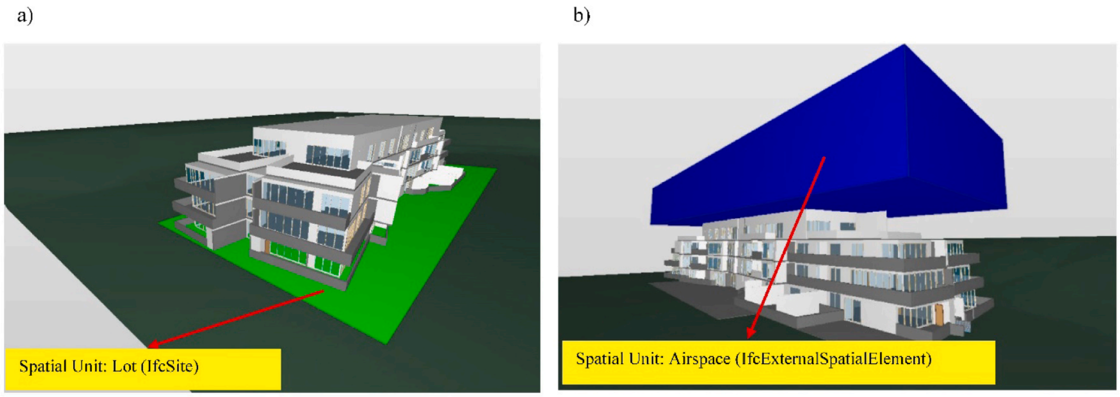

Fig. 8. Spatial units for a) land parcels and b) airspaces rights in the BIM environment.

concepts (IfcZone) in the BIM environment. In the example shown in Fig. 9, one basic administrative unit is defined for two volumes of space (e.g. an apartment unit and a carpark space) with the same ownership right. In addition, the attributes for the related RRR and party information are also shown to illustrate that BIM environment is capable to manage data elements defined in the administrative and party packages of LADM. To demonstrate complex basic administrative units in the BIM environment. a common property zone comprising several shared spaces is shown in Fig. 10.

Fig. 11 shows different IFC entities which can be used for modelling points, boundary face strings and boundary faces. In the BIM viewer (Solibri) used in our study, only the boundary faces can be represented visually. However, for boundary face strings and points, the source text of the IFC file shown to demonstrate how these concepts are implemented in BIM models. In Fig. 11, we highlighted the row numbers that link different IFC entities in different colours to facilitate its understanding.

Fig. 12 shows an example of boundaries that go through the centreline of the walls. In this example, the boundary is located in the middle of a wall which separates a commonly owned area (corridor) from a private ownership space (apartment unit).

The legal boundaries are not always defined based on physical objects. Fig. 13 shows examples of the legal boundaries that are not identical to the physical objects. In the multi-storey buildings, these types of legal boundaries are usually defined for separating the ownership of car park spaces.

5. Discussion

The idea behind the work presented in this article was integrating legal and physical dimensions of buildings based on existing international standards. This study focused on integrating legal and physical information using a data modelling approach since data models are the basis for data integration. For modelling physical aspects of buildings, our choice was the open IFC standard in the BIM domain while LADM is considered as the appropriate conceptual data model for managing legal information.

There has been a significant leap in adoption of BIM and its open standard, IFC, for managing the lifecycle of buildings. This signifies the fact that the adoption of LADM in the built environment, especially in complex multi-storey building, should be linked with the BIM environment. Therefore, we suggested a new approach for integrating legal and physical dimensions of buildings based on encoding and embedding LADM concepts into the IFC standard using the extension mechanisms provided in IFC. Mapping LADM concepts onto the IFC standard would provide the ability to link a wide range of ownership data elements, such as spatial units, RRR and party information, to lifecycle information defined in BIM environment. IFC standard is the underlying basis for

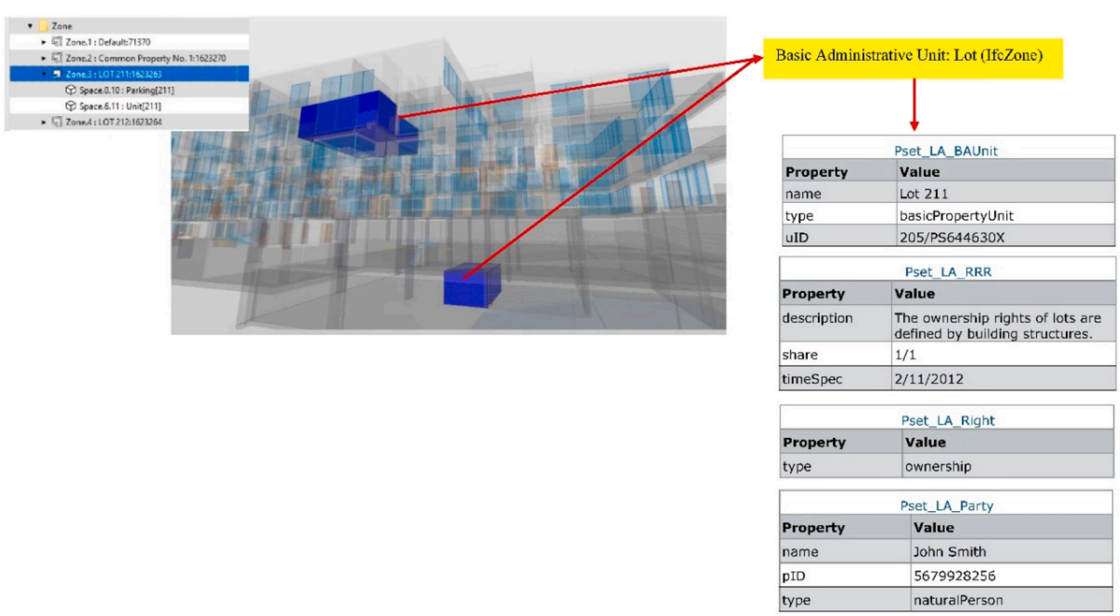

Fig. 9. A basic administrative unit with its relevant RRR and party information.

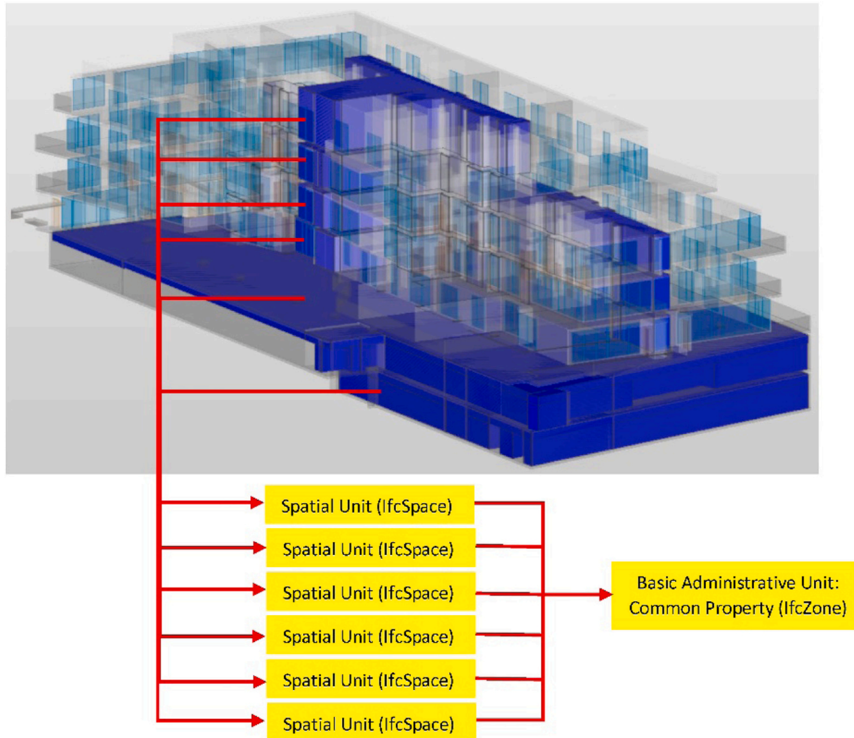

Fig. 10. A complex basic administrative unit (common property) in the BIM environment.

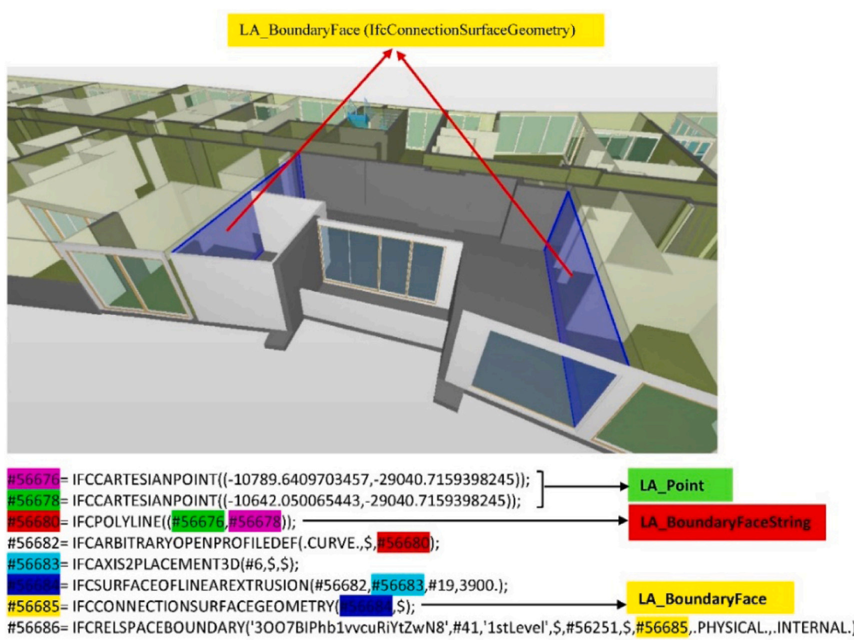

Fig. 11. Examples of IFC entities suggested for modelling points, boundary face strings and boundary faces.

managing building lifecycle in an open and interoperable way. This approach would unlock the value of legal information beyond 3D digital property registration. For instance, legal rights, restrictions and responsibilities in property management, after its registration, can be easily determined if legal concepts of LADM are integrated with physical and lifecycle data elements. This would also help other land development stakeholders to better communicate and exchange information with land administration actors, such as land surveyors or land registries.

Integration of LADM concepts into the IFC standard would motivate developed jurisdictions to adopt LADM for upgrading their cadastral systems into 3D digital information environments. In some jurisdictions, such as Australian states and territories, architectural components of buildings are mainly used for defining the spatial location of ownership boundaries. Integration of LADM and IFC standards would broaden the adoption of LADM standard in covering various jurisdictional approaches for 3D land and property management.

Having a unified 3D data environment, which is based on LADM and

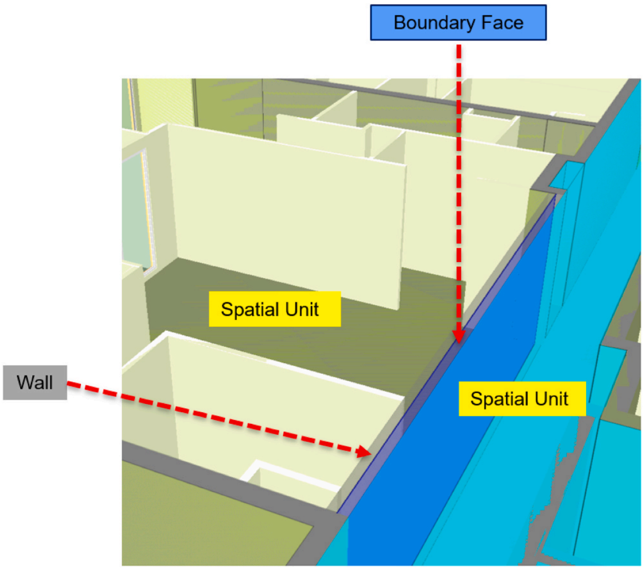

Fig. 12. An example of boundary line passing through the centreline of a wall.

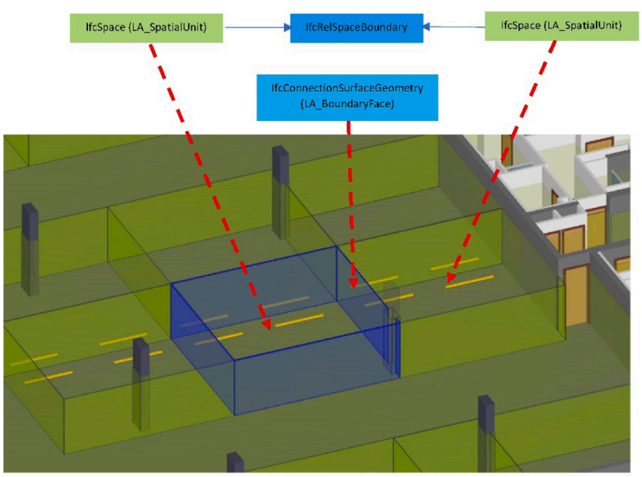

Fig. 13. Legal boundaries which are not identical to physical objects.

IFC standard, for managing legal and physical dimensions of buildings will reduce current issues in finding and retrieving legal boundaries and RRR information from multiple data sources. This will lead to a better understanding of an array of different ownership rights that exist in a complex built environment. The added benefit to stakeholders will be the ability to find legal and physical data in one place. This will also increase the number of non-experts using 3D cadastral systems, supporting better community participation in managing buildings.

Despite the above-mentioned benefits, there remain challenges in our proposed approach for linking LADM and BIM environment. These challenges are:

Establishing effective interactions between two standardization experts in LADM and IFC standards. Mapping LADM concepts into IFC standard requires a good understanding of standards by both expert groups.

Integrating the jurisdiction specific requirements for the proposed IFC and LADM mapping can be challenging since each jurisdiction has its own legal data requirements and mapping the spatial and semantic complexity of these legal requirements can be a significant challenge when implementing integrated LADM-IFC data model for particular jurisdiction.

Mapping the relationships between legal concepts defined in the LADM into the IFC standard. Currently, in LADM, various semantic relationships between different entities are defined and these relationships may change when transforming them into the equivalent IFC classes. In IFC, relationships are defined as entities while LADM does not consider any entity for relationships between legal concepts. For example, the relationship between 'LA_BAUnit' and 'LA_AdministrativeSource' is defined based on UML notations. However, in the IFC standard, 'LA_BAUnit' is mapped into 'IfcZone' and 'LA_AdministrativeSource' is modelled using 'IfcDocumentInformation'. The relationship between 'IfcZone' and 'IfcDocumentInformation' is defined using 'IfcRelAssociatesDocument' entity which corresponds to the relationship between 'LA_BAUnit' and 'LA_AdministrativeSource'. Fig. 14 illustrates this challenge.

6. Conclusions

The major contribution of this study was mapping LADM concepts into BIM environment by using relevant entities and allowed extension mechanisms in the IFC standard. A prototype BIM model was implemented to demonstrate that LADM concepts can be embedded into IFC without significant disruption in the current structure of IFC. Future investigations will be conducted by applying this integration on real-world case studies, particularly in building developments with complex architectural design. This will help us refine the proposed approach in line with real-world practices, which would subsequently result in a more feasible approach for integrating legal and physical dimensions of buildings in a 3D digital environment.

In future work, the creation process of legal boundaries referencing building elements can be automated in the integrated IFC file. For example, an algorithm should be developed to provide the user with the ability to choose which face (interior, median or exterior) of a building element is used for delineating the legal boundary.

CRediT authorship contribution statement

Behnam Atazadeh: Conceptualization, Methodology, Software, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Hamed Olfat:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Abbas Rajabifard:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Mohsen Kalantari:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Davood Shojaei:** Methodology, Investigation, Data curation, Writing - original draft, Writing - review &

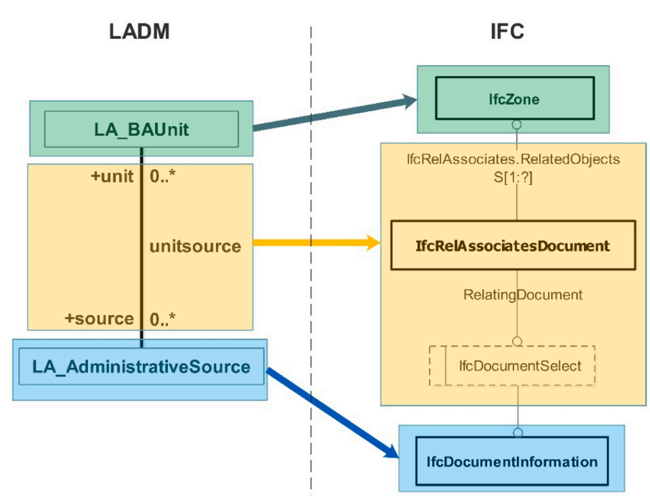

Fig. 14. Challenge in mapping LADM relationships to the IFC standard.

editing. **Afshin Mesbah Marjani:** Software, Visualization.

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