Reviewing the Literature on the Tripartite Cycle Containing Digital Building Permit, 3D City Modeling, and 3D Property Ownership

Abstract

There is an increasing trend for digitalization because of the developments in Information and Communications Technologies (ICTs). One of the topics that digitalization might be helpful is the building permit issuing that has some drawbacks in terms of the duration of finalization, a large number of documents, and the transparency of processes. Another topic is the need for updating three-dimensional (3D) city models that are beneficial for the effective management of urban areas in the sense of a wide range of subjects such as land-use planning, disaster response, and underground infrastructure monitoring. Apart from these topics, 3D land administration that copes with the ownership problems due to the ever-increasing existence of multilayered buildings in the built environment is gaining importance. Many studies mention that the interrelation among these topics can be advantageous because of exploiting the common digital building models namely Building Information Models (BIMs). It is therefore focused on a research question as follows: Is there a potential for integrating the digital building permit procedures, 3D city model updating, and 3D registration of property ownership as a tripartite cycle? This paper accordingly aims to review the scientific literature on the vision of the tripartite cycle to provide an insight into possible integration among its parts. The methodology contains an elaborate examination of the previous research that is collected from scientific databases and is categorized based on aspects of the tripartite cycle. Following the discussion of the literature, the recommendations are provided in the sense of the vision of the tripartite cycle.

Keywords

Automatic Compliance Checking, Geographic Information Systems (GIS), Building Information Modeling (BIM), 3D Cadastre, 3D City Model, 3D Land Administration.

1. Introduction

The concept of a "Smart City" is currently accepted as the solution to problems related to modern societies, for example, fast urban population growth, low right of habitation, high energy consumption, air and noise pollution, and gas emission. To solve these problems, geospatial intelligence can support the smart city concept by providing information about location, neighborhood, field, object, network, event, granularity, accuracy, meaning, and value as well as a complete representation of these features (Kuhn, 2012; Roche, 2014). Since Geographic Information Systems (GIS) and Science (GIScience) hold a great number of open standards, paradigms, principles, and techniques (e.g., (OGC, 2020a)) that provide the representation, processing, visualizing, and sharing spatial aspects of the built environment, they can deal with the citizen-centric problems in smart cities (Degbelo et al., 2016; Roche, 2017, 2016). Although GIS has the capability to apply spatial analysis about the environment at a large scale, it remains incapable of detailed representation and designing of all aspects of buildings. On the other side, Building Information Modeling (BIM) is used to digitally represent the structures' physical and functional features. Moreover, BIM encapsulates the highly elaborate construction information about buildings in terms of semantic and geometric details, but it might fail to satisfy in providing geographically delineation of extended features in the surrounding environment (Amirebrahimi et al., 2016; Wang et al., 2013).

Another important topic is the Land Administration Systems (LASs) that can benefit from GIS and BIM in the context of the smart city. These systems provide a thorough process that includes determining, recording, and disseminating information with regard to land tenure as well as land value and land use (Williamson et al., 2010). LASs exploit cadastral data models in order to spatially manage Rights, Restrictions, and Responsibilities (RRRs) in association with a part of land or ownership (de Vries et al., 2015). The alterations that occur in land parcels are a subject of LASs because they not only affect ownership rights but also change the built environment with respect to 3D spatial data (Lemmen et al., 2015). In this context, building permits that should be approved by local and regional agencies according to detailed laws and regulations, and 3D city models are important issues related to the aforementioned alterations associated with land parcels.

Existing building permit procedures cannot fulfill the needs of complex metropolises where a vast number of new construction projects are being put into practice, because these procedures lack sufficient functionality and effectiveness. The shortcomings of the building permit procedures are typically due to the use of two-dimensional (2D) printing, manual reviews, and challenging submission approaches (Macit İlal and Günaydın, 2017; Tan et al., 2010). Although building designs are created in 3D by using prevalent data types, institutions that are responsible to carry out building permit issuing generally demand 2D data. This might interrupt and impair the efficiency of the building permit procedures since it cannot be benefitted from highly detailed 3D building designs (Malsane et al., 2015; Preidel and Borrmann, 2018). This issue is important because the examination of the building permit is sometimes realized by taking the immediate surroundings of the buildings into account as there can be several restrictions on different subjects such as green spaces, historic spaces, protected areas, and disaster susceptible areas (Shahi et al., 2019). It is clear that 3D designs are more useful than 2D designs for this examination because 2D data do not enable clear and uncomplicated compliance checking regarding underground, aboveground or volumetric features related to buildings. In other words, 3D digital building models can hold a significant potential to contribute to enabling more integrated compliance checking due to their highly detailed semantic and spatial data. Also, the submission procedures can be more efficient and easier for both applicants and inspectors if digital building models are used (Noardo et al., 2020c). Therefore, the advantage that arises from the use of the integration of BIM and GIS techniques comes out to ameliorate the existing building permit procedures (Chognard et al., 2018; Noardo et al., 2022; Olsson et al., 2018).

The contribution to the 3D city model database is yet another reason to use the building models that are generated by using BIM or GIS. Keeping updated the 3D city models is a challenging task because of rapid alterations in living areas (Biljecki et al., 2015). The use of as-built digital building models can significantly contribute to this task (Noardo et al., 2020a). Another important point is related to the registration of legal rights associated with both land parcels and constructed buildings. The existing building permit procedure is over with the construction of the building in a wide range of countries but the potency that derives from the use of as-built models in updating the cadastral database is taken no notice (Guler and Yomralioglu, 2021a). There is a strong potential to put into practice efficient LASs in the sense of 3D cadastre through the use of as-built digital building models in the registration of condominium ownership (Grant et al., 2020; Rajabifard et al., 2019; van Oosterom et al., 2020).

The main objective of this paper is to investigate and review the tripartite cycle. The vision of the tripartite cycle is composed by the authors after generally screening the literature on digital building permit procedures, 3D city modeling, and 3D cadastre topics. It is seen in this screening that researchers in most of the previous studies mention in their papers separately that it would be helpful if these topics are integrated. Considering the cyclical process that enables efficient interrelation between digital building permit procedures, 3D city model updating, and 3D registration of property ownership can contribute to the exchanging, updating, and storing of the information digitally, this research aims to elaborately examine the existing efforts in the literature regarding the parts of the cycle in order to bring to light if/how the tripartite cycle can be put into practice. The presented study can contribute to the existing body of knowledge by providing:

- ✓ the perspective of the tripartite cycle that can assist the digitalization of building permit procedures, update of 3D city models, and 3D registration of condominium rights.
- ✓ the review of previous endeavors on each part of the cycle.

After the introduction to the topic of the paper, Section 2 introduces the vision of the tripartite cycle. Section 3 presents the research method and Section 4 informs readers on the quantitative analysis in the paper. The next three sections examine digital building permit procedures, 3D city model updating, and 3D registration of property ownership, respectively. The eighth section discusses the existing efforts in the sense of the vision of the tripartite cycle. Finally, the last section concludes the paper by relaying information about future directions.

2. The Vision of the Tripartite Cycle

The presented paper focuses on the review of the tripartite cycle that is introduced in general and can be seen in Figure 1. This cycle is composed of three parts: digital building permit procedures, 3D city model updating, and 3D registration of property ownership. 3D digital models are highly important to comprehensively manage multilayered cities. Using and updating the 3D national databases that countries try to compose in detail is therefore in the vision. These databases are formed based on the CityGML (OGC, 2021a) standard widely as this standard is developed to digitally represent the urban areas. 3D national or city databases should contain the features regarding building, construction, land use, and vegetation at least to support the building permit procedures that benefit from built environment data in the urban planning context. Another database in the cycle is related to zoning plans. Creating and storing these plans digitally are considered worldwide to integrate different stakeholders that deal with spatial data in the sense of planning and development. One of the possible formats that is used to store zoning plans is Geography Markup Language (GML).

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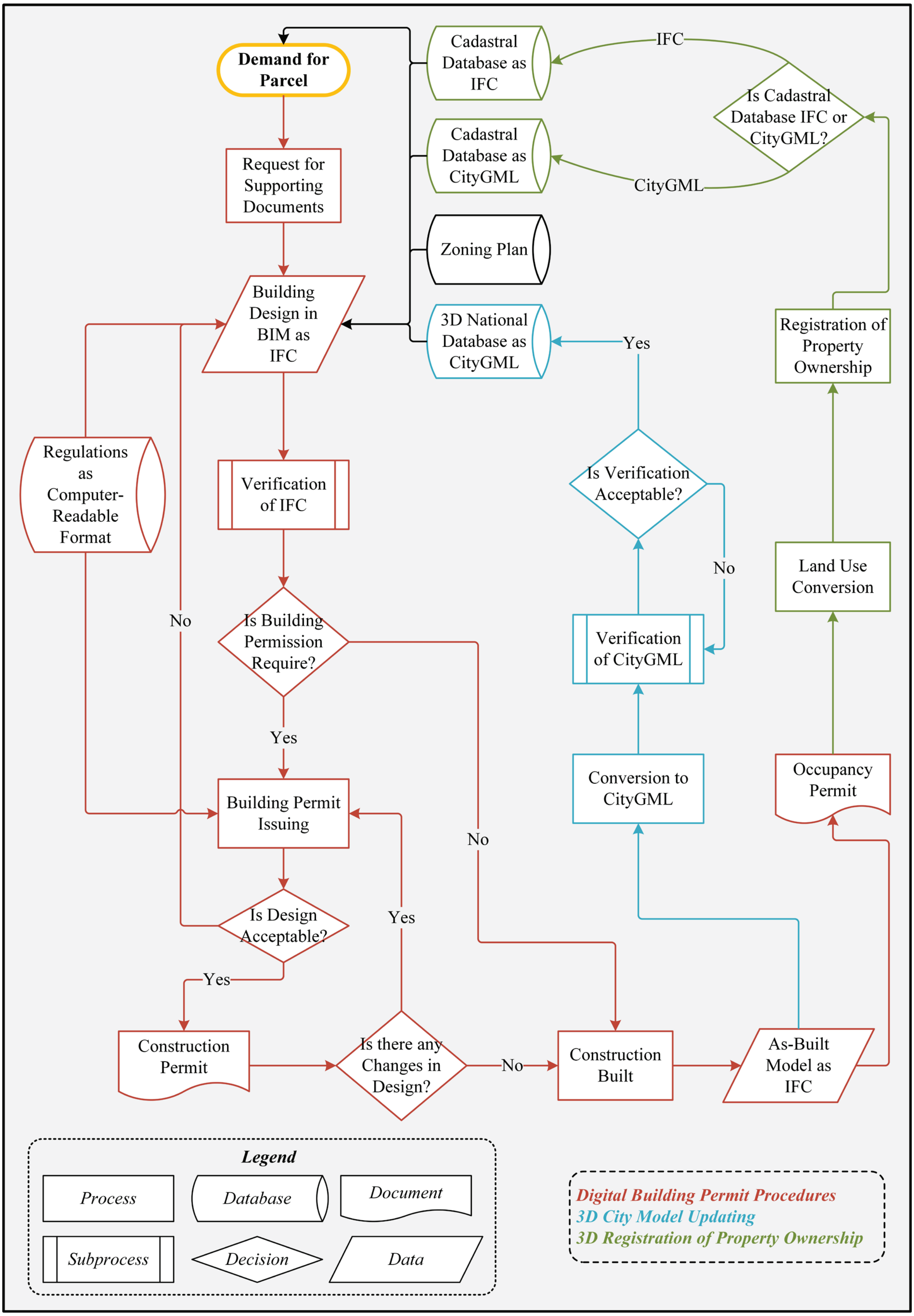

Figure 1. The general schema of the vision of the tripartite cycle.

Storing and sharing zoning plans not only aid the digitalization and automation of building permitting, but also help to make the process more efficient by providing significant and useful data in the design phase of the buildings. A cadastral database that digitally stores the registration information related to land and buildings is another essential database in the vision. As can be seen from Figure 1, the cadastral database may be composed based on two possible standards, namely Industry Foundation Classes (IFC) (ISO, 2018) and CityGML since there are important studies that aim to model ownership rights by exploiting these standards. They are used to model legal rights with their physical counterparts through enriching and combining Land Administration Domain Model (LADM) (ISO, 2012) standard that provides a common basis for features and relationships regarding parties and RRRs in LASs. Considering the tripartite cycle contains a wide range of processes, the organization and administration within the cycle are of significance to achieve an uninterrupted mechanism. Active cooperation among different organizations such as building permit and urban administration offices, and cadastral agencies is important in terms of data exchange. Exploiting the e-government applications that allow governing bodies to control and manage various tasks can be thus used to execute processes within the parts of the tripartite cycle.

The building permit procedure starts with the demand for new building construction or renewal in the relevant parcel. It is significant to note here that a great number of stakeholders including real estate agencies, vendors, architects, owners, construction inspectors, banks, and funding institutions involves in this procedure. To start the process, it is needed different kinds of data, for example, cadastral data, zoning plan data, and built environment data (e.g., ownership and use type of the parcel, planned depth and the maximum height of the building, locations of the underground infrastructure facilities and historical sites). These kinds of data are vitally important since they form a basis for the development of cities and countries. Whereas cadastral registration provides essential information on ownership regarding parcels and apartments for both citizens and administrators in terms of societal and economic maintenance, zoning plans show remedial insights for efficient use of land. The management of urban and rural areas can be more effective for prospective investments thanks to the analysis results that are obtained by using built environment data. Continuity of sustainability can thus be enabled because the actions related to the environment, finance, and culture are governed powerfully. Regarding this, most countries endeavor to compose Spatial Data Infrastructure (SDI) relying on the data application schemas that are compatible with 3D spatial data models, so as to enable effective and sustainable land and governmental administration. According to the vision, buildings can be designed in IFC format that is developed for ensuring the interoperability between actors since the adaptation of BIM and its open standard (i.e., IFC) has been highly increased recently in different sectors, especially in Architecture, Engineering, and Construction (AEC) industry. It can be noted here that the vision focuses on the buildings/building structures rather than infrastructure objects such as tunnels and bridges that do not require a building permit for construction.

The verification of the designs of these buildings is performed in order to ensure their use in building permit procedures. One of the modelling verifications is possibly based on criteria that are defined according to the countries' specific needs with respect to the rules and requirements in their legal codes. Other possible verification can be based on the modelling guidelines that are formed using Model View Definition (MVD) (buildingSMART, 2022) for example. The process continues depending on whether the design needs to building permit or not. If it is not needed for a building permit, the building construction can start without delay. Otherwise, the audit should be performed to determine whether the design is compatible with building regulations or not. An electronic submission system and automatic building checking can be used within this period. A database that contains the rules in legal documents as the machine-readable format is quite important. In this context, there are a large number of efforts that aim to put into practice the implementation of an integrated building permit process by benefiting from digitalization and automation with the aim of enhancing the quality of the process for different involved parties (e.g., local agencies, applicants, and building control officers). If the design contains any unsuitableness, it is returned to the submitter to be made necessary changes. After, the new audit is actualized to give building permission. In addition to this, if the design changes during construction, a new building permit should be got. The occupancy permit that allows to reside and exploit infrastructure facilities in the building should be received if it is required.

After the construction is completed, the as-built model in IFC format can transform the CityGML in order to update the national or regional 3D city model database. The transformation continues with the verification of the CityGML model. By doing this, it can be made a significant contribution to the quality of the geospatial database that requires a huge effort to preserve its up-to-dateness. Noteworthy to mention that the conversion from IFC to CityGML is a challenging issue owing to the differences regarding such as semantics, representation approach, and targeted scale for modelling. These differences result in some problems such as geometric inconsistency and deficiency on semantics in generated data. Identifying the desired level of detail for output in the first place and validating the IFC before conversion are possible solutions that might improve the conversion quality (Noardo et al., 2020b). Increased inclusiveness between standard specifications of IFC and CityGML is also beneficial for efficient transformation. The use of an as-built IFC model rather than an approved model in building permitting is of significance for updating 3D digital models realistically.

In the tripartite cycle, property ownerships can be registered to cadastral databases as 3D through as-built 3D models such as IFC models; therefore, up-to-date and accurate dataflow can be achieved between various agencies (e.g., real estate valuation department). The land-use type conversion that should be applied in the cadastral database after obtaining the occupancy permit is crucial to store the correct cadastral information regarding parcels because essential economic activities (e.g., taxation) are utilized using such information. Also, the condominium plans that are approved by building permit offices should be sent to the land registry offices for registration of property ownership related to buildings. If this alteration does not become reality, the cycle will be incomplete. In this phase, the condominium ownerships related to the new building are registered by using as-built models depending on whether the national cadastral database is in IFC or CityGML format and hence the tripartite cycle is completed.

Building permit procedures as part of the cycle are promisingly related to the registration of property ownership, namely, land administration, because the process occurs in the land parcel (Guler and Yomralioglu, 2021b). It is needed to cadastral information at the beginning of the building permit procedures. The strong point of the cycle is that it has the flexibility to adapt to different countries since it provides a comprehensive framework. LADM is one of the most crucial efforts for putting into practice the 3D LAS transition as it can be integrated with data standards that are developed for physical modeling and representation of the objects. It can be also customized based on the countries' or regions' specific needs pertaining to cadastre and land registry. Considering that 2D graphics remain incapable for the representation of property ownerships in complex buildings, the vision of the tripartite cycle has important potential thanks to the generated 3D as-built building models.

3. Research Method

Since this paper aims to elaborate on the practicality of the vision of the tripartite cycle, a literature search is conducted based on the three main parts of the cycle namely digital building permit procedures, 3D city model updating, and 3D registration of property ownership. The *Scopus*[1] and *Web of Science*[2] databases are exploited for literature research since these databases

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[1] https://www.scopus.com/search/form.uri?display=basic&zone=header&origin=#basic

[2] https://www.webofscience.com/wos/woscc/basic-search

are accepted as comprehensive and trustworthy and used by different researchers to carry out a literature review. Several keywords are used to extract the papers through different search query combinations in terms of the *"title, abstract, and author keywords"* because separate studies focus on different topics related to the vision of the tripartite cycle. These query combinations include keywords as follows: *"building permit"*, *"compliance checking"*, *"code checking"*, *"GIS"*, *"BIM"*, *"3D city model", "3D cadastre",* and *"3D property ownership"*. The conference proceedings of long-established organizations such as the International Federation of Surveyors (FIG) are also examined as part of the review because they are not indexed by *Scopus* and *Web of Science* databases. The last decade is accepted as most state-of-art and taken into account by a large number of researchers that conduct literature reviews (e.g., (Chrysafiadi and Virvou, 2013; Felsberger and Reiner, 2020; Reza et al., 2014)). The papers that are published between 2010 and 2020 are therefore considered in this review paper. Duplicated and irrelevant papers are eliminated by first screening so that final papers that are included in this paper are obtained. Subcategories are identified for each part of the tripartite cycle by considering the aspects on which the papers focus, as shown in Figure 2. These subcategories form the subheadings of the sections in the paper.

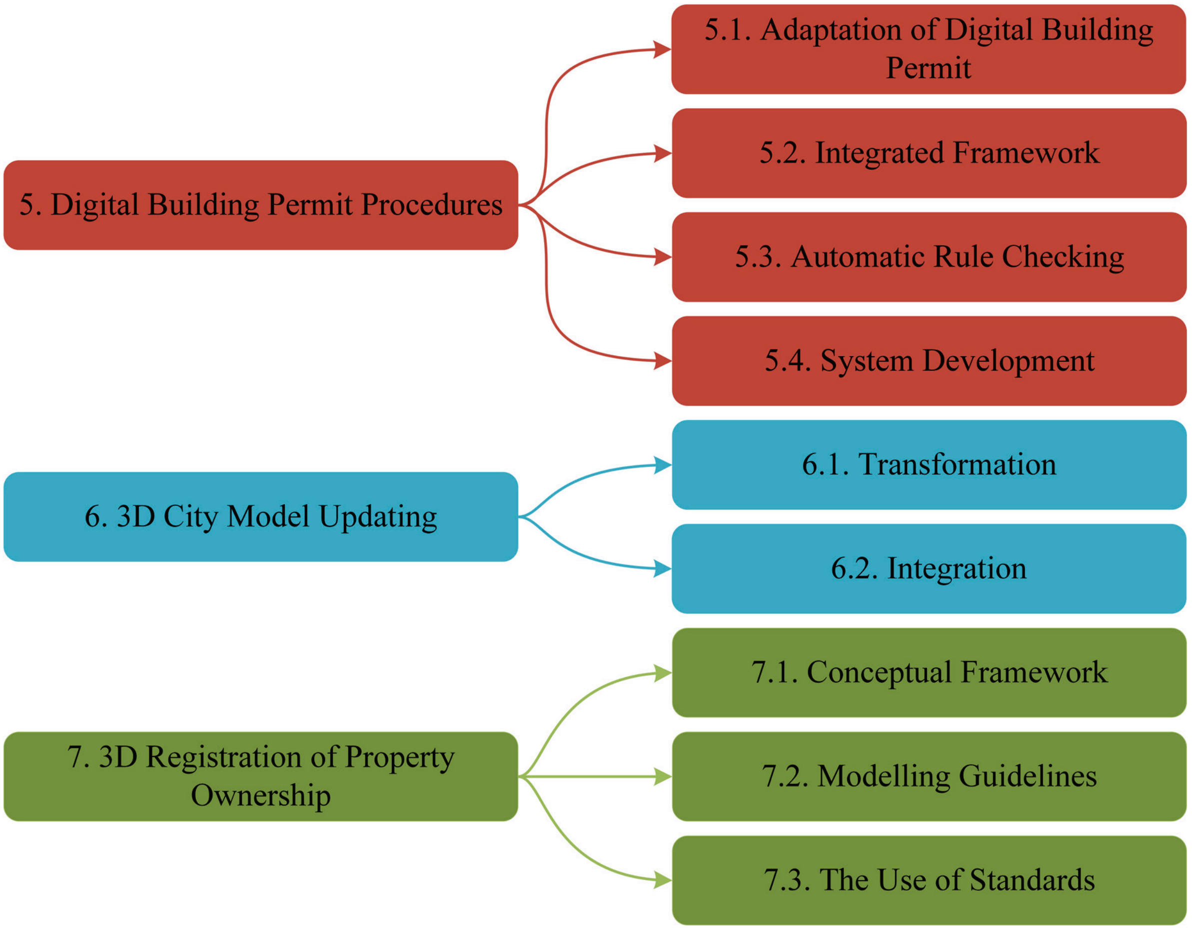

Figure 2. The main parts of the tripartite cycle and their subcategories.

4. Quantitative Analysis

The quantitative analysis is carried out to reveal the current trends in the literature on the vision of the tripartite cycle. Figure 3 shows that there is a growing research trend on parts of the tripartite cycle. The number of papers related to 3D registration of property ownership is higher than the papers belonging to other parts in the last five years. Digital building permit procedures have more papers than 3D city model updating except in 2011 and 2020.

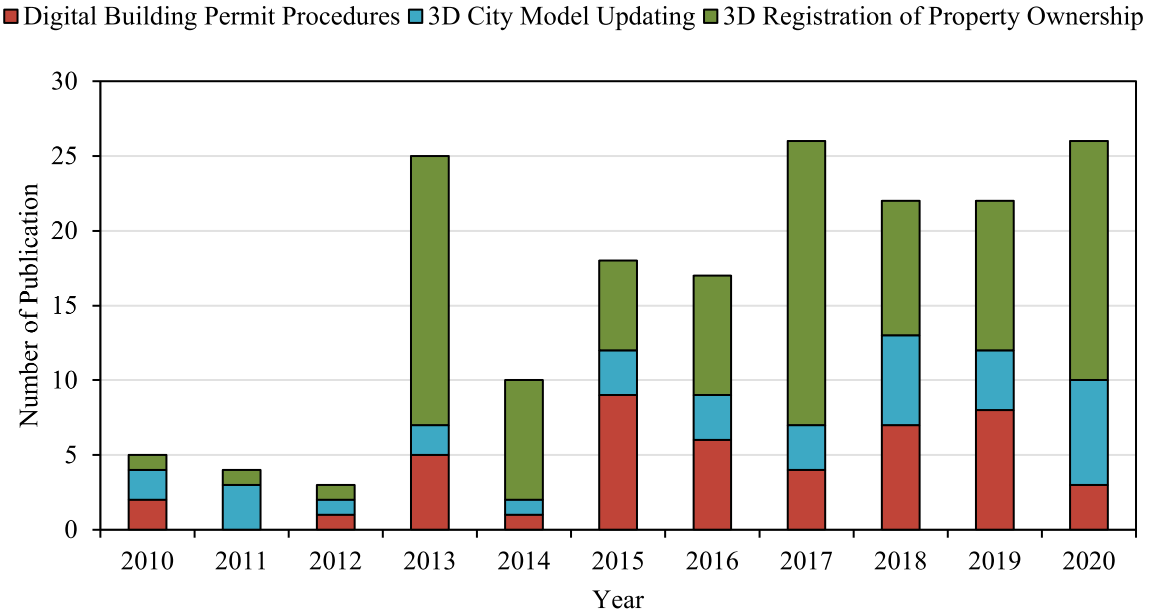

Figure 3. The number of publications by year pertaining to parts of the tripartite cycle.

The occurrences of keywords by year can show an insight into the current research trend in the literature. A heatmap that shows the number of occurrences of keywords is thus created (Figure 4). Keywords of the papers in all three parts of the tripartite cycle are included in the heatmap. As can be seen from Figure 4 that "*BIM*" and "*3D Cadastre*" are the most used keywords. This is not surprising as the adaptation of BIM is rapidly growing in various sectors, and there is a need for 3D cadastre transition due to the complexity of the built environment. "*IFC*", "*CityGML*" and "*LADM*" are following these keywords and hence this shows the importance of the international standards. "*GIS*" is another keyword that is used frequently since it is one of the dominant domains in the tripartite cycle.

Figure 4. The occurrences of keywords that are used at least four times in total.

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5. Digital Building Permit Procedures

The vision of the tripartite cycle includes the digital building permit procedures. In this regard, the existing efforts are examined in a broad range of subjects including the adaptation of digital building permit, integrated framework, automatic rule checking, and system development (see Table A.1 for an overview of the reviewed research). Figure 5 shows an automated and integrated building permit procedure proposed in the research reviewed for this paper (Shahi et al., 2019).

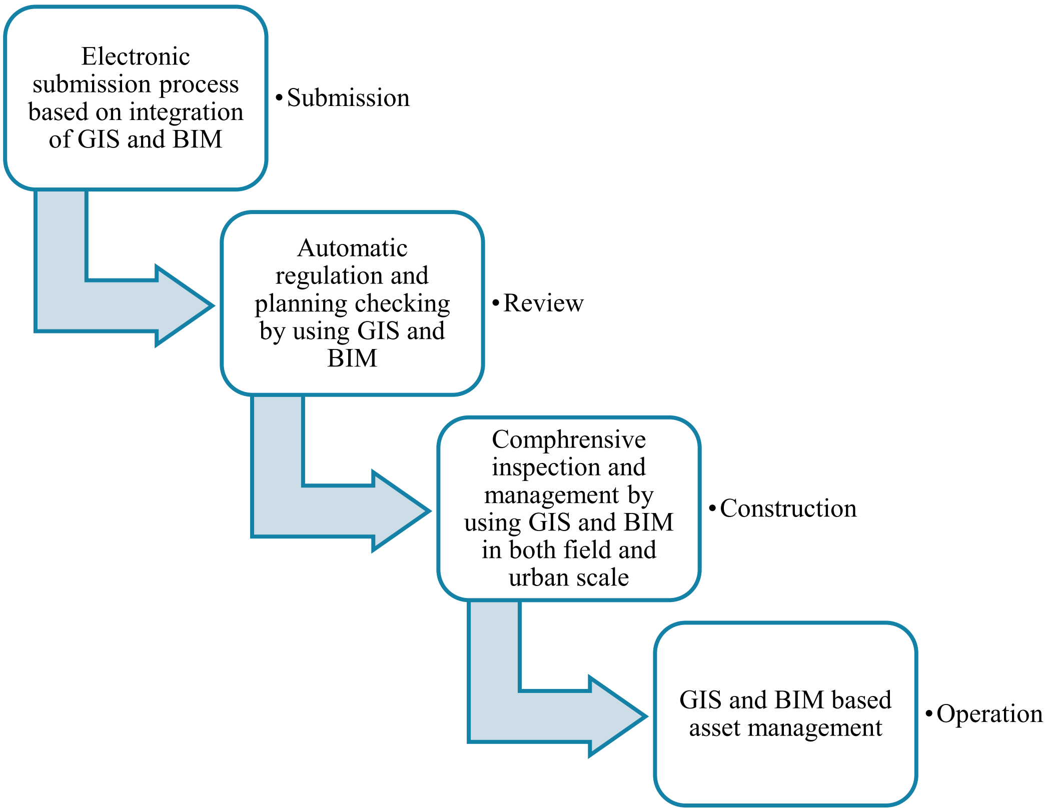

Figure 5. Automated and integrated building permit issuing (adapted from (Shahi et al., 2019)).

5.1. Adaptation of Digital Building Permit

Bringing to light the current state of the adaptation of the digital building permit process provides insight for increasing the adaptation in both countries where advanced level procedures are already applied and countries where actions are taken to improve the process recently. The level of adaptation of building permit issuing in different countries is researched by various scholars (Allmendinger and Sielker, 2018; Beach et al., 2020; Juan et al., 2017; Lee and Chiang, 2016). Possible reasons for the unsuccessful practice of digital building permitting are found as inadequate training about the system, inefficient project design, insufficient motivation, and miscommunication between engineers and employees (Bellos et al., 2015). It is important to examine the successful systems that are operated in the countries such as Norway and Singapore to create a plan for efficient implementation of digital building permitting in other countries since it is seen that systems have different characteristics and should keep pace with technological and modeling improvements (Hjelseth, 2015). Creating a roadmap for a country distinctively is researched and also suggested to help the transition to digital building permitting (Beach et al., 2020). Dimyadi and Amor (2013) underline the need for a system that meets the requirements of the construction sector by ensuring the standardization and abolition of manual alterations, in order to facilitate the adaptation. It is also mentioned that increasing the adaptation of BIM-based building permitting is beneficial in the context of urban planning since BIM models in IFC format can be used to secure more detailed information about the environment and building (Allmendinger and Sielker, 2018).

5.2. Integrated Framework

The integrated framework that benefits from the advantages of BIM models for planning, design and execution, validation, clash detection, code checking, and temporal project management is proposed with the aim of improving building permit procedures (Ciribini et al., 2016; Mouloud et al., 2019). On the other hand, regulations on building permitting widely include rules regarding both buildings and the built environment. Restrictions on shadow and noise levels are examples of such rules. There is an incremental research trend for the integrated framework that exploits GIS and BIM domains for digital building permitting (Noardo et al., 2020a; Shahi et al., 2019). In the smart urban management context, Shahi et al. (2019) propose a framework that benefits from the integration of GIS and BIM for both automatic code checking and facility management to enhance the capabilities of jurisdictions. CityGML and IFC, which are dominant open standards for GIS and BIM domains respectively, are commonly investigated for the digitalization of building permit procedures. It is drawn attention in the related studies that CityGML models can be helpful to make urban planning-based checks more objective and that BIM models in IFC format can be exploited in 3D spatial planning checks (Abdel Wahed et al., 2012). In this regard, the applicability of a CityGML ADE is exemplified in the German context (Benner et al., 2010).

It is touched on in the paper (van Berlo et al., 2013) that supporting the IFC by the majority of the software is substantial to increase the applicability of BIM-based spatial planning. The improvement of the accuracy differences, transformation, georeferencing, and Coordinate Reference System (CRS) combability between IFC and CityGML is suggested as being beneficial for digital building permitting (Onstein and Tognoni, 2017). It is for example proposed that the georeferencing of as-built BIM models that are converted to CityGML can be done by benefitting from field measurements (Olsson, 2018; Olsson et al., 2019). It is also underlined that the collaboration between different agencies and departments that responsible for building permitting can be enabled by means of an integrated framework that exploits web-based services (Chognard et al., 2018). Olsson et al. (2019) highlight that the controlling of building design in the planning phase is significant to achieve a more flawless building permission process. It is moreover specifically focused on using the BIM data of newly constructed buildings to keep up-to-date the city geodatabase in the sense of an integrated framework (Noardo et al., 2020a).

5.3. Automatic Rule Checking

Automation composes a cardinal part of digitalization. Figure 6 illustrates the automatic code checking process that is actualized by using BIM models.

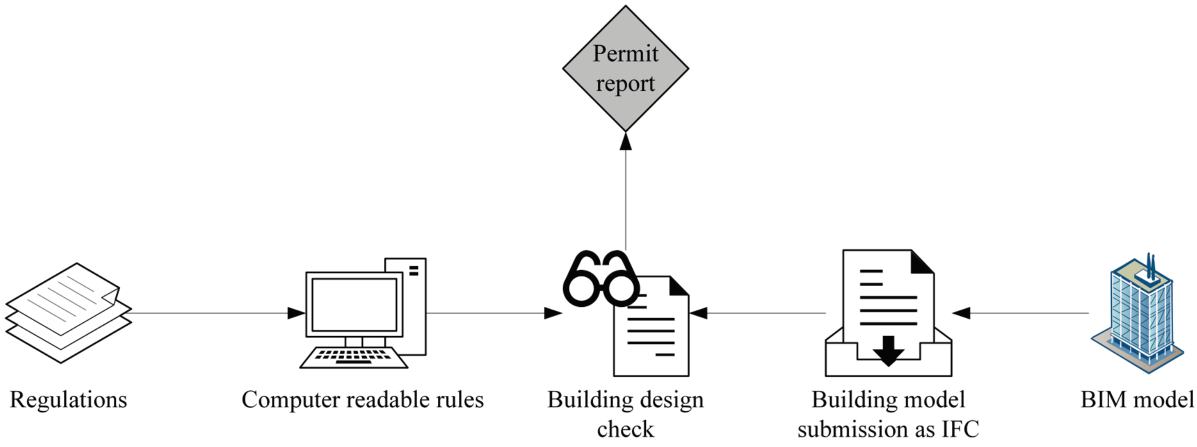

Figure 6. The automatic code checking process that is based on BIM.

Preidel and Borrmann (2018) mention that transparency and feasibility can be enriched with the help of the white-box approach and underline that it is needed to continue working toward fully automatic code checking because many of the building regulations are not prepared to enable their conversion to computer-workable form. Different approaches are therefore researched to obtain the most effective solution, for example, context-free grammar language (Uhm et al., 2015) and logic expressions (Fan et al., 2019). Scholars benefit from graphical and visual programming-based approaches as well (Dimyadi et al., 2016; Ghannad et al., 2019; Kim et al., 2019). Preidel and Borrmann (2015) highlight that increased visual language libraries can be more efficient for automated code compliance studies. Researchers obtain prospering accuracy results using Natural Language Processing (NLP) as well (S. Li et al., 2016); however, they also mention that there is a need for a vast amount of manual processing (Zhang and El-Gohary, 2016) and there is a need to compare the proposed methodologies with other semi-automatic methods (Zhang and El-Gohary, 2017). The manual process and the proposed methodology present the same evaluation for rule checking in the paper where Semantic Web Rule Language (SWRL) is applied in order to create metadata on regulations (Beach et al., 2015). The domain-specific languages are also proposed to automatically check the rules in different contexts such as interior designs (Sydora and Stroulia, 2020). BIM-based approaches are used for deep foundation (Luo and Gong, 2015) and green construction projects (Jiang et al., 2019).

Query language, namely SPARQL is used and also extended such that it meets the query needs for rule checking (Zhang et al., 2018; Zhong et al., 2018). It is pointed out in the paper (Solihin and Eastman, 2015) that more efficient code checking performances could be obtained by defining prerequisites within the BIM environment, especially by using IFC. By means of a compact system that is developed using logic-rule-based methods, artifactual regulations related to buildings are converted into computer-readable formats, including XML and JSON (Lee et al., 2016). Some scholars focus on exploiting the GIS-based data. For example, Olsson et al. (2018) obtains convincing results compared to the manual calculation by integration of BIM and GIS data for automatic code checking regarding building area and building height. In another paper (Brasebin et al., 2016), it is proposed an approach that consists of the geometric representation of objects and their relationships to formalize the regulations related to building permit using various standards namely Object Constraints Language (OCL), CityGML, and Infrastructure for Spatial Information in Europe (INSPIRE) specifications for the cadastral parcel. Automatic code checking is studied by different researchers to increase safety in construction in the context of building permit requirements (Choi et al., 2014; Zhang et al., 2015). It is highlighted in the study (Zhang et al., 2013) that there is a need for more real-time safety checking since constructions have a large number of changes in the building phase. Malsane et al. (2015) state that if automatic process checking is used, it will ease the procedure in terms of time, workforce, and process monitoring.

5.4. System Development

The development of efficient systems is significant for the digitalization of the building permit process within the tripartite cycle. It is highlighted that the cloud and web-based systems that rely on open-source technologies are beneficial to enhance the effectiveness of building permitting in smart cities where digitalization takes a vital part since these systems ensure that multiple government agencies get involved in the procedure (Eirinaki et al., 2018; Koo et al., 2013; Martins and Monteiro, 2013; Wahed, 2017). Mena et al. (2010) mention that the use of a language standard within a system is also helpful for the documentation lifecycle in digital building permitting.

6. 3D City Model Updating

The tripartite cycle contains the update of 3D city models by exploiting the as-built BIM models. The previous efforts that focus on the efficient combination of GIS and BIM-based models are therefore investigated from different perspectives including transformation and integration (see Table A.2 for an overview of the reviewed research).

6.1. Transformation

The studies on this topic mainly focus on the transformation of IFC into CityGML (Sebastian et al., 2013). Whereas some scholars introduce an approach that simplifies the semantic solving and concentrates the geometric representation for better conversion (Adouane et al., 2020), some of them offer a solution that applies the linguistic and text mining techniques (Ding et al., 2020). Researchers propose several CityGML ADEs that are specifically developed to provide better transformation (Cheng et al., 2013; de Laat and van Berlo, 2011; Deng et al., 2016; Hijazi et al., 2011; Stouffs et al., 2018). Ohori et al. (2017) mention that the use of the most common geometry classes is more beneficial than the conversion of all IFC entities to CityGML. It is also underlined that more advanced IFC standard and BIM models with fewer errors can improve the effectiveness of transformation practices between BIM and the GIS environment. It is drawn attention in the paper (Ohori et al., 2018) that one of the important reasons for unsuccessful conversion between IFC and CityGML is the incompleteness of designed BIM datasets and there is a need for a more sophisticated IFC standard. Donkers et al. (2016) highlight that the suggested methodology that enables to convert buildings in IFC to CityGML contains some improvisations about geometries. The usability of SketchUp that enables to export of 3D BIM models is also investigated for transforming IFC to CityGML (Boyes et al., 2017; Floros et al., 2018; Kardinal Jusuf et al., 2017). There also exists research that concentrates to bidirectional transformation between IFC and CityGML (Cheng et al., 2013; El-Mekawy et al., 2011). For example, Deng et al. (2016) compares the conversion results of the proposed framework with previously suggested methods in the literature and concluded that the framework has a lot of advantages by comparison with other methods in terms of bidirectional mapping, levels of detail, extensions to schemas, and semantic information.

The approaches that allow converting IFC to shapefile datasets are also proposed in the literature (Zhu et al., 2020, 2019a, 2019b). In addition, Xu et al. (2020) propose an implementation approach that combines the IFC and 3D Tiles (OGC, 2019) datasets, which is an OGC standard, so as to enhance the web-based processes and analyses. Biljecki and Tauscher (2019) underline that all of the error types do not affect the conversion quality uniformly because separate researchers benefit from specific entities of 3D data models to complete the spatial analyses. The intermediate models and workflows that enable better interoperability and transformation are also developed (El-Mekawy et al., 2012; Knoth et al., 2019; Strobl et al., 2018; Xu et al., 2014). For example, Kang (2018) purposes a conceptual mapping standard named "B2GM" and pointed out that if the aim of the performed study is determined before the data transformation, this will provide to be obtained more beneficial data in the GIS domain. It is aimed in the paper (Jetlund et al., 2020) to create a Unified Modeling Language (UML) model that provides transformation between core models, namely IFC and ISO/TC 211.

6.2. Integration

Uggla and Horemuz (2018) compare various methods by benefiting from current IFC standard entities in terms of scale distortion, scale factor, angular distortion, and project height and mention that the proposed transformation method by Borrmann et al. (2017) shows practicable performance in comparison to the other coordinate transformation methods. Diakite and Zlatanova (2020) propose an approach that can automatically georeference the BIM models in a GIS environment with centimeter precision. It is investigated in the paper (Boyes et al., 2015) to transfer the generated BIM models in Autodesk Revit into Oracle relational databases (RDBMS) as the IFC standard by benefiting from Feature Manipulation Engine (FME) software and python scripting. Geiger et al. (2015) who examine generalization by transforming the IFC entities related to building and by forming datasets in different LoDs inform that some windows are not correctly created in the LoD3 model because of the wrong Boolean operation. Different platforms in both domains, namely GIS and BIM that allow users to execute various demands such as spatial analysis, visualization, clash detection, query, and export are proposed (Beetz et al., 2010; Hijazi et al., 2010). It is also researched how to benefit from Airborne Laser Scanning (ALS) dataset for integrating the BIM into 3D city models (Sun et al., 2020). Karan et al. (2016) who develops a framework based on modeling IFC classes by means of Resource Description Framework (RDF) and Web Ontology Language (OWL) suggest that the selection of similar features for unmatched exchanges will improve the quality of integration. It is shown in the paper (Kang and Hong, 2015) that a system architecture based on the Extract, Transform, and Load (ETL) method is more efficient than the existing manual method according to evaluations of users.

7. 3D Registration of Property Ownership

The tripartite cycle gives an opportunity for both the transition to 3D cadastre and the preservation of the up-to-dateness of the cadastral database. It is therefore investigated how tenures can be registered to this database as 3D in the context of the cycle based on the different topics, namely conceptual framework, modelling guideline, and the use of standards. Figure 7 illustrates the 3D registration of property ownership by using as-built building models (see Table A.3 for an overview of the reviewed research).

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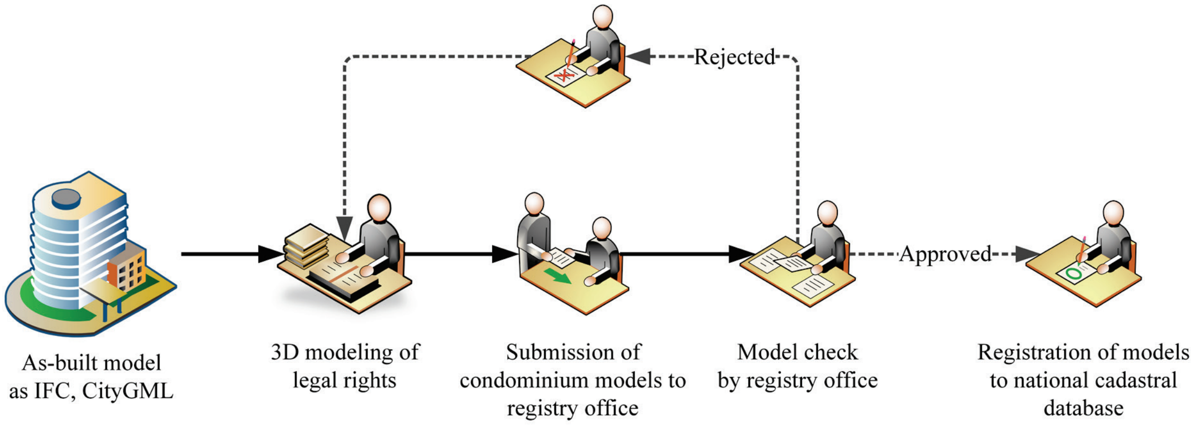

Figure 7. The 3D registration of property rights.

7.1. Conceptual Framework

The workflows that enable to implementation of 3D representation and registration of ownership rights are important for the vision of the tripartite cycle. In this sense, the aims of the vision and the spatial development lifecycle overlap since both of them include the use of as-built models for 3D cadastral registration (Kalogianni et al., 2020). There exists a large number of studies in different countries that aims to 3D cadastre transition that provides up-to-date 3D cadastral registration within the tripartite cycle (Ayazli et al., 2011; Çoruhlu et al., 2016; Griffith-Charles and Sutherland, 2013; Gulliver et al., 2017; Kim et al., 2015; Loshi, 2018; Vučić et al., 2017). Regarding this transition, van Oosterom (2013) highlights the significance of the shared concept and terminology, definition of 3D spatial units, visualization, and formal semantic in the context of 3D registration of property rights. Ghawana et al. (2020) suggest the raising of the awareness of public and relevant institutions for the transition to 3D cadastre in the context of Delhi, India. The current applicability level with respect to 3D registration of property ownership is examined as it is essential to put forward effective frameworks (Ho and Rajabifard, 2016; Isikdag et al., 2015). For example, Shojaei et al. (2016) note that the e-Plan system that is used for digital cadastre in Australia is suitable for 3D registration of property ownership, but features for modeling of curved shapes need to be improved. It is underlined in the paper (Drobež et al., 2017) that the current dataset is more than sufficient for the transition to 3D cadastre in Slovenia. Olfat et al. (2018) highlight that the reusing of data is quite important for 3D digital cadastre. It is come to the conclusion in the paper (Rajabifard et al., 2018) that there is a need for a spatial model that has a holistic approach to efficiently represent both legal rights and their physical counterparts. The data sources such as LiDAR, remotely sensed images, and crowdsources data are investigated in the context of 3D cadastre (Drobež et al., 2016; Gkeli et al., 2019; Griffith-Charles and Sutherland, 2020). In this regard, Jazayeri et al. (2014) emphasize that photogrammetry, laser scanning, mobile mapping, Unmanned Aerial Systems (UAS), and BIM are important data sources for 3D cadastre. These data sources can be considered as an option to preserve the up-to-dateness of the cadastral database that is updated within the tripartite cycle.

In addition, having a time dimension in the database is crucial for the temporal management of cadastral registration (Döner et al., 2010). It is also suggested the use of spatial planning objects within the 3D cadastral data model (Bydłosz et al., 2018). The existence of a solid legislative background is another important topic for both 3D cadastre transition and registration of condominium rights within the tripartite cycle. In this sense, researchers focus on the elaboration of which updates should be applied to legal frameworks and legislations to enable the efficient implementation of 3D digital cadastre (Dimopoulou and Elia, 2013; Ho et al., 2013; Kitsakis et al., 2019; Kitsakis and Dimopoulou, 2020, 2017, 2014; Larsson et al., 2020; Paasch et al., 2016). It is highlighted that the comparative analyzes that include cases from different countries can substantially contribute to the realization of 3D cadastre that is beneficial for legal systems in terms of constructing and financing (Paulsson, 2013; Paulsson and Paasch, 2013). Jaljolie et al. (2018) underline that there is a need for enhanced and updated legislative guidelines for realizing the 3D cadastre in the context of Israel. The system prototypes that enable the physical implementation of proposed conceptual models in 3D cadastre context are developed in different studies. An approach that contains the use of Computer-Aided Design (CAD), GIS, and Database Management Systems (DBMS) is proposed as a way of registering condominium rights (Floros et al., 2017; Siejka et al., 2014; Spirou-Sioula et al., 2013). A web-based visualization prototype is developed for 3D cadastre specifically (Shojaei et al., 2018, 2015). A prototype exploiting the NoSQL database is suggested for 3D cadastre as this type of database has noteworthy compatibility with current data formats of today, for example, JSON (Višnjevac et al., 2019, 2017). Guo et al. (2013) develops a porotype for 3D cadastre in Shenzhen, China, and stated that there is a need for legal alteration for a steady system.

7.2. Modelling Guidelines

Navratil and Unger (2013) investigate the usability of different height systems for 3D cadastre and note that there is no system that fits all countries. It is thus suggested that a suitable height system can be selected based on the characteristics of the country. Conformal Geometric Algebra (CGA) expressions are suggested to enhance topological analyzes between 3D cadastral objects (Shi et al., 2019; Zhang et al., 2019, 2016). Wang et al. (2017) point out that the three transparency levels in the visualization of 3D property units are sufficient. Ying et al. (2019) develops an algorithm that improves the visualization of 3D objects that can be used for the representation of 3D property units. It is suggested in the paper (Tekavec and Lisec, 2020a) to use the SFCGAL 3D functions for data extraction from 3D cadastral and BIM data. Karki et al. (2013) develop validation rules for the 3D registration of property ownership. Soon (2013) proposes an OWL-based approach that enables the representation of user roles in land administration processes such as registration of land titles and submission of survey plans. Knoth et al. (2020) propose a new approach that exploits solid models for updating the 3D digital cadastral database.

7.3. The Use of Standards

A great number of researchers create a country profile of LADM or extend it to enable conceptual reference for 3D cadastral registration (Alkan et al., 2021; Alkan and Polat, 2017; Janečka and Souček, 2017; Kalogianni et al., 2017; Lee et al., 2015; Radulović et al., 2019, 2017; Stoter et al., 2013; Vučić et al., 2020). Cemellini et al. (2020) develop a 3D cadastre prototype that is web-based and compatible with LADM. Pouliot et al. (2013) carry out a comparative analysis that contains the 3D registration of condominiums in keeping with LADM in France and Canada. It is underlined that there is a need for an improvement in documentation of the standard, and a significant amount of information for precise modeling.

Given that LADM focuses on logical spaces, and CityGML and IFC standards aim to model physical parts regarding city objects, a great number of studies integrate it with these standards to delineate legal rights with their physical counterparts (Atazadeh et al., 2018a; El-Mekawy and Östman, 2012; Góźdź et al., 2014; Li et al., 2016; Oldfield et al., 2017; Soon et al., 2014; Sun et al., 2019). Rönsdorff et al. (2014) highlight that it is important to be taken specific regulations of countries into consideration during the ADE development process. LADM is also used for the registration of legal rights using crowdsourced data that is obtained by a mobile application (Gkeli et al., 2020). The IndoorGML (OGC, 2020b) standard, which is developed for indoor navigation, is integrated with LADM for 3D cadastre purposes (Alattas et al., 2017). It is also suggested in the paper (Tekavec and Lisec, 2020b) that the IndoorGML dataset can be created using existing cadastral data.

It is underlined in various studies that using the as-built BIMs for 3D registration of apartment rights in the buildings offers a solid potential (Andrée et al., 2018; Atazadeh et al., 2016). Oldfield et al. (2016) also suggest that the as-built BIM models should be used for the correct 3D cadastre database because the designed BIM models can change during the construction process. El-Mekawy et al. (2014) underline that although it is a growing interest in BIM that is considered as the most comprehensive and detailed building modeling system, there is a need for integration of various standards such as IFC, CityGML, and LADM. The IFC standard is used and also expanded to meet the modelling needs of 3D cadastre (Atazadeh et al., 2017c, 2017a, 2017b; Atazadeh et al., 2018b; Shin et al., 2020; Sladić et al., 2020). It is concluded in the paper (Atazadeh et al., 2017d) that the pure models might perform better performance for visualizing and querying in comparison with other models, yet the integrated models should have the capability to ensure a more heuristic and visually enhanced representation of 3D legal rights. Atazadeh et al. (2019) highlight that the 3D queries can be powerfully used by different agencies and stakeholders related to buildings, for example, cadastral offices and building permit compliance inspectors.

In addition, a 3D cadastral model that specifically aims to provide 3D modelling of property rights is proposed (Aien et al., 2015, 2013b, 2013a). The created LandXML files that represent 3D multi-topologic objects for land administration applications are validated using LADM (Thompson et al., 2017). The usability of the CityGML standard in the representation of cadastral rights is investigated by creating an extension or a specific ADE since it is developed and widely used to digitally model the built environment (Cagdas, 2013; Li et al., 2015; Ying et al., 2017). For example, Ying et al. (2014) point out that CityGML models can be used as a beneficial data source in place of troublesome and costly data acquisition methods such as laser scanning and surveying. A Git-based versioning approach that transforms buildings from the perspective of 3D cadastre is proposed through extending CityGML (Eriksson et al., 2021).

8. Discussion

The vision of the tripartite cycle mainly relies on conducting the information flow and process digitally. Digitalization inevitably affects the different organizations that deal with the management of the built environment. AEC companies, land registry and cadastre agencies, and departments related to urban planning and the environment distinguish among these organizations. The manipulation of digital data makes necessary the interrelation between different applications that these organizations are responsible for. It is needed for example up-to-date information on both cadastral registration and built environment to properly design a new building depending on the requirements regarding building permitting. The digitalization of building permit procedures is thus a timely topic that is promoted by administrations on both the country and regional levels. The literature, therefore, focuses on the ways that provide the efficient application of digital building permitting. Examining the previous studies show that the adaptation of digital building permitting differs among countries; however, it is agreed with that digital building permitting can facilitate and enhance the related processes. For example, European Union (EU) countries try to practically achieve the aim of the utilization of the digital building permit procedure since it takes part in prospective strategies and directives of the European Commission (EC) (European Commission, 2020, 2014).

Automatic building design checking is an important factor that contributes to the digitalization of the building permit procedures. The approaches that aim to automate the compliance checking within building permitting come to the fore since the BIM models, especially IFC data, offer an important opportunity to query semantic and geometric information with respect to building parts. At this point, it is vital to note that code checking can be applied to building designs during their development phase instead of the final state so that cumulative errors can be prevented. It can be mentioned that more work is required to achieve fully automatic code checking even though there exist promising results by applying Artificial Intelligence (AI) methods, for example. This is because it is needed manual interference for converting the rules that might result in ambiguities to machine-readable format. There is nevertheless an increasing trend towards exploiting the integrated frameworks that include GIS and BIM-based models since regulations that cover zoning contain the rules with regard to the surrounding environment and the building itself. Noteworthy to mention that the interrelations between GIS and BIM-based models can be more efficient to comprehensively check these rules. Strengthening the harmonization between open standards is thus pivotal for better implementation of mentioned frameworks.

Literature review reveals that web-based systems that evolved from e-submission applications are highly needed and important for the efficient implementation of digital building permitting as part of the digital government transition. It is evident that the adaptation of BIM augments the presence of as-built digital models. This creates a significant opportunity to update 3D city models using these models. Accordingly, it is unsurprising that there are a large number of studies on integration and transformation perspectives, considering that the sustainable management of the built environment requires to manipulation of both GIS and BIM-based models. It is important to point out that a few studies directly mention updating the 3D building models by means of as-built BIM models. The literature mostly concentrates on the transformation of IFC data to CityGML data through exploiting the ADE mechanism of the CityGML commonly. It is seen that the differences between the standards with respect to modelling approach and coordinate systems hinder lossless transformation. In this regard, CityJSON (Ledoux et al., 2019; OGC, 2021b) that aims to facilitate the use of CityGML data models for different purposes by working out the practical problems related to the implementation and conversion of these models is accepted as an official OGC standard recently. It is crucial to mention that the coordinate transformation, georeferencing, and database management are of significance for better integration of BIM-based models to GIS environments to ensure lossless 3D city model updating within the tripartite cycle. Furthermore, the integration of BIM and GIS-based models in web platforms is quite important to carry out city model updating digitally.

The literature review also shows that countries endeavor to put into effect 3D LASs that are based on international standards. It can be noted at this point that the approaches that allow generating efficient models representing the legal rights and their counterparts, and that enable queries within these models are significant to put into practice the reliable cadastral database. Whereas LADM is the prominent standard due to providing an important, common basis conceptually, the usability of CityGML for a physical representation of RRRs is investigated by integrating it with LADM. It can be noted that a great amount of research concentrates on exploiting the BIM models as they allow the delineation of legal rights adequately. It is clearly seen that the standards that ensure interoperability are of significance for 3D registration of ownership, digital building permit procedures, and 3D city model updating as well. This leads to increasing the importance of integration between standards that are developed by different aims in terms of the application scale and scope. The interoperability of LandInfra (OGC, 2016) with CityGML and IFC is an important example of such integration (OGC & buildingSMART International, 2020). It is important to note here that the new version of CityGML, which is approved recently, is designed as being more compatible with IFC and LADM by providing a new *space* concept and considering the suggestions in the previous research (Kutzner et al., 2020).

9. Conclusion and Prospective Directions

This paper performed a comprehensive review by concentrating on digital building permit procedures, 3D city model updating, and 3D registration of property ownership subjects to gain a sense of the vision of the tripartite cycle.

It is crucial to note that the translation of rules in codes and regulations regarding building permitting into computer-readable format needs specific attention because of its difficulty that may result from ambiguities in the legal texts. Also, the transformation between BIM and GIS-based models is highly significant for the smooth update of 3D city models within the tripartite cycle. The international standards are essential for the effectual implementation of 3D registration of condominium rights within the tripartite cycle since they not only provide a robust basis that can be extended to meet the requirements of application areas but also ensure interoperability. The ever-increasing adaptation of BIM in the AEC industry paves the way for using them for 3D cadastre (Olfat et al., 2019; Stoter et al., 2017). In addition, BIM-based query approaches are important to ensure the accessibility of current information within the context of the tripartite cycle (Barzegar et al., 2020). Moreover, although there is a growing trend for transition to digital building permit procedures, it is pivotal to identify whether the stakeholders from different sectors have the required basis for the transition. Considering the digitalization of building permitting mostly relies on the use of BIM, specifically IFC models, BIM should be adapted sufficiently in involved sectors and industries, for example, the AEC, land administration, and spatial planning. It can be consequently concluded that the literature review reveals that there is a significant potential to realize the tripartite cycle because digital data and information are jointly utilized within the cycle.

Future work can concentrate on finding efficient ways for putting into practice the vision of the tripartite cycle illustrated in Figure 1. Contractors and architects should be able to obtain essential supporting documents to start building design through web-based platforms. Cadastral databases, zoning plans, and 3D city models can be efficiently serviced by competent authorities to achieve this. In this sense, research can focus on which data format is most suitable to maintain and disseminate necessary data for digital building permit procedures. It is important to note that the data formats should be interoperable in order to provide an effective and realistic design. For this reason, updated versions of standards and newly proposed international standards should be detailedly examined to use for digital building permit processes.

The use of a central electronic submission platform for building permits could be investigated to improve effectiveness. The regulations should be converted to a computer-readable format to automate the building permit processes. This issue is a challenging task for different countries because existing studies mostly worked on English-based natural language processing techniques. Future studies can concentrate on building regulation conversion into different languages. The building designs should be verified by using open-source tools to offer an economic and flexible solution for administrations. In this connection, the levels of detail for different stages of the building permit procedure should be determined by analyzing the essential data for processes. Construction inspectors should be able to access the as-built design to properly audit. At this point, research can focus on web-based solutions to allow the representation and querying of IFC-based building models. It is essential to enable the efficient conversion between BIM and GIS-based data formats. New conversion methodologies should be examined and tested to provide reliable data for 3D city models.

Research can zoom in the use of approved condominium plans in the building permit process for property registration. The 2D-based cadastral registration is widely used in the large majority of countries; however, the literature review reveals that 3D cadastre has become significant and necessary in today's cities. In this sense, future work should focus on the use of as-built models in the 3D registration of property ownership. This issue will be an important advantage that is provided by the vision of the tripartite cycle.

In addition, incentive policies and understandable guidelines should be developed in order to efficaciously implement the vision of the tripartite cycle. In this regard, the collaboration among academia, industry, and government agencies will prove beneficial to make more realistic decisions. Moreover, the characteristics and necessities of jurisdictions should be considered when producing policy and making legal amendments. In this context, a top-down approach could be effective if the sectors related to building permitting are ready to use 3D digital building models. It is therefore significant to acknowledge that the best way that makes countries successful in the implementation of the tripartite cycle can differ depending on the practice area. Data interoperability is of vital importance since different government agencies play a part in the cycle.

Last but not least, there is a need for a holistic approach that considers building permit issuing, city models, and cadastral databases as interacting issues in the use of 3D digital models. In this way, effective and feasible policies that are sufficient for both administrations and citizens will be produced. Noteworthy to mention that recommendations mainly presume that countries have or will have digital information because of the ever-increasing trend for digitalization worldwide. It should, however, be kept in mind that other types of non-digital documents that are included in the process regarding such as decision-making and information processing might exist. Finally, the next studies can carry a step forward in the analysis in this paper by considering studies that are published after the paper is prepared.

Appendices

Table A.1. Publications, their proposed solutions, and related aspects in the paper in the sense of digital building permit procedures.

Publication	Proposed Solution	Aspect
(Beach et al., 2020)	Investigates the current state of the art on automation of building permit in the UK and proposes a roadmap	Adaptation of Digital Building Permit
(Bellos et al., 2015)	Examines the electronic building permission system works in the context of e-government strategies in European Countries	
(Hjelseth, 2015)	Investigates two successful digital building permit process solutions, including Norway and Singapore, in terms of the Integrated Design and Delivery (IDDS) framework	
(Juan et al., 2017)	Analyzes whether architecture firms in Taiwan have an adequateness to use an electronic building permit system that benefits from BIM	
(Allmendinger and Sielker, 2018)	Examines how BIM and urban planning can contribute to each other and proposes to use the electronic submission systems	
(Dimyadi and Amor, 2013)	Underlines the need for a system that ensures the standardization and abolition of manual alterations to meet	

	the requirements in the context of the efficient construction sector	
(Lee and Chiang, 2016)	Examines whether the new code checking system based on BIM in Taiwan meets the expectations of different stakeholders who play a part in building design	
(Shahi et al., 2019)	Proposes a framework that contains both digital and automatic building permit and facility management using BIM and GIS-based models	Integrated Framework
(Onstein and Tognoni, 2017)	Suggests an improvement for CRS compatibility of the IFC4 data schema and mvdXML for GIS and BIM integration in building permit context	
(Abdel Wahed et al., 2012)	Proposes the GIS-based approach for urban planning regulation controls and building permit procedures	
(Benner et al., 2010)	Proposes a CityGML ADE for building license processes as a case study in Germany	
(van Berlo et al., 2013)	Examines the usability of 3D BIM models that are designed by architects in the context of the integration to 3D spatial planning works	
(Chognard et al., 2018)	Examines to use of reference building files formatted as IFC format for building permit process in terms of data exchange with CityGML	
(Olsson et al., 2019)	Provides control of building design in the planning phase and to keep up to date the city geodatabase by using BIM data	
(Noardo et al., 2020a)	Proposes the use of integration of GIS and BIM in building permit procedures	
(Mouloud et al., 2019)	Proposes a framework that includes planning, design and execution, and validation to improve the current permit system	
(Ciribini et al., 2016)	Elaborates on the construction project that aims to benefit from advantageous features of BIM, including model validation, clash detection, and code checking as well as temporal project management within Italy	
(Brasebin et al., 2016)	Proposes an approach that consists of the geometric representation of objects and their relationships	Automatic Rule Checking
(Olsson et al., 2018)	Investigates how the integration of BIM and GIS data can contribute to automatic building permit issuing	
(Choi et al., 2014)	Proposes an automated regulation checking based on IFC for evacuation purposes	
(Uhm et al., 2015)	Translates the rules using context-free grammar language for automatic design checking in a request for proposal (RFP) context	
(Luo and Gong, 2015)	Develops a BIM-based compliance checking approach for deep foundation construction projects	
(Jiang et al., 2019)	Proposes an automatic rule checking approach based on mvdXML in green construction code checking context	
(Zhang et al., 2018)	Proposes an approach that extends SPARQL functions for querying IFC data in rule checking context	
(Fan et al., 2019)	Develops a rule evaluation interface based on logic expressions	
(Zhong et al., 2018)	Proposes a methodology that automatically checks environmental conditions of the buildings against regulations by using sensor data and SPARQL	

(Sydora and Stroulia, 2020)	Proposes a domain-specific language to check rules in the interior design context	
(Preidel and Borrmann, 2018)	Mentions that transparency and feasibility can be enriched with the help of the white-box approach	
(Zhang et al., 2015)	Develops a framework for automatic code checking in a construction safety context	
(Zhang et al., 2013)	Proposes a procedure that uses automatic safety checking in the design phase of construction projects for preventing fall accidents	
(Malsane et al., 2015)	Examines how automatic rule checking according to regulations can be achieved by benefiting from IFC models within England and Wales	
(Ghannad et al., 2019)	Proposes a framework that integrates the LegalRuleML and Visual Programming	
(Preidel and Borrmann, 2015)	Proposes a code compliance checking methodology that is based on visual language and BIM	
(Beach et al., 2015)	Develops a semantic approach that uses SWRL (Semantic Web Rule Language) and IFC	
(Solihin and Eastman, 2015)	Classifies the building codes according to their computation complexities	
(Dimyadi et al., 2016)	Proposes a graphic approach based on open standard graphical language in fire engineering context	
(Lee et al., 2016)	Proposes a compact system that allows converting of artifactual regulations related to buildings into computer-readable formats, including XML and JSON, by means of logic-rule based methods	
(Kim et al., 2019)	Proposes an approach that allows representing the machine-readable building codes using visual symbols for architects and rule viewers	
(Zhang and El-Gohary, 2016)	Proposes a methodology that consists of extraction of related concepts from regulations, selection of the most similar IFC entities that match with these concepts, and finding of suitable relationships according to regulations as a means of utilizing natural language processing and machine learning	
(S. Li et al., 2016)	Proposes an approach that is based on the GIS and uses natural language processing in order to prevent the accidents that stem from insufficient compliance checking, especially underground objects	
(Zhang and El-Gohary, 2017)	Proposes a methodology that aims to fully automate the compliance checking by utilizing natural language processing and logic reasoning	
(Mena et al., 2010)	Proposes an approach that uses the Internet, XBRL, and new Spanish standard for efficient documentation lifecycle	System Development
(Koo et al., 2013)	Develops a web-based management system including building permit management	
(Eirinaki et al., 2018)	Develops a cloud-based building permit system that is beneficial for smart cities	
(Martins and Monteiro, 2013)	Develops a computer system that contains a database and a graphical user interface that allows controlling of the regulation compatibility of designed structures in terms of hydraulics	
(Wahed, 2017)	Suggests a methodology that is based on GIS and web services	

Table A.2. Publications, their proposed solutions, and related aspects in the paper in the sense of 3D city model updating.

Publication	**Proposed Solution**	**Aspect**
(Zhu et al., 2019a)	Aims to enhance the previously developed Open-Source Approach (OSA), which is for geometry transformation of Industry Foundation Classes (IFC) into the shapefile format.	Transformation
(Zhu et al., 2019b)	Converts into shapefile by developing an automatic multipatch generation algorithm (AMG)	
(Zhu et al., 2020)	Aims to automate the conversion of IFC clipping representation into the shapefile format	
(Strobl et al., 2018)	Proposes a core model that can be expanded for user requirements	
(Knoth et al., 2019)	Proposes a workflow that allows exchanging of BIM and GIS models regardless of the data type of the source file	
(Jetlund et al., 2020)	Creates a pattern that improves the transformation between IFC and ISO/TC 211 schemas	
(Xu et al., 2020)	Proposes an implementation approach that combines the IFC and 3D Tiles datasets, in order to enhance the web-based processes and analyses	
(Adouane et al., 2020)	Introduces an approach that simplifies the semantic solving and concentrates the geometric representation for better conversion of IFC into CityGML	
(Ding et al., 2020)	Offers a solution that applies the linguistic and text mining techniques for transforming IFC datasets to CityGML models	
(de Laat and van Berlo, 2011)	Investigates the transformation of IFC models to CityGML by creating CityGML ADE named GeoBIM in order to provide to the integration of BIM and GIS	
(El-Mekawy et al., 2011)	Proposes a generic model to enable the bidirectional transformation between IFC and CityGML	
(El-Mekawy et al., 2012)	Proposes a Unified Building Model (UBM) environment that integrates the building-related model elements of IFC and CityGML by identifying featured classes, so as to enable the interoperability between these standards and to prevent deficiencies because of conversions	
(Cheng et al., 2013)	Develops a strategy that makes possible bidirectional model transformation between IFC and CityGML by the way of providing practicable parser design	
(Donkers et al., 2016)	Suggests a conversion approach between IFC and CityGML buildings that takes geometric features into consideration	
(Deng et al., 2016)	Proposes a framework that can parse the input model and transfer it to another requested model	
(Ohori et al., 2017)	Studies how BIM models in IFC format can be efficiently transformed into CityGML by applying open-source coding in terms of practice and data level	
(Kardinal Jusuf et al., 2017)	Creates the transfer methodology between IFC and CityGML for building elements by using FME in order to integrate these two systems in the context of sustainable urban built environment applications	
(Ohori et al., 2018)	Explores feasible methodologies that allow the automatic conversion of IFC datasets to CityGML, that facilitate the integration of subsurface information into the design phase of	

	infrastructure projects, and that enable the correct georeferencing of IFC models	
(Floros et al., 2018)	Proposes a workflow that facilitates the transformation of IFC models to LOD 4 in CityGML by utilizing FME software	
(Stouffs et al., 2018)	Proposes an approach that determines the specific data modeling necessities by taking users into consideration, using the Triple Graph Grammar (TGG) method, and creating CityGML ADE to cover the expectations relative to usage area and to attach the IFC entities that are unrequited in CityGML	
(Kang, 2018)	Proposes a conceptual mapping standard named "B2GM" to meet the expectations of specific use cases and that prevents ineffective integrated data models	
(Biljecki and Tauscher, 2019)	Investigates the quality of transformation between IFC and CityGML by elaborating possible error sources that stem from features of inputs, conversion techniques, and software	
(Sebastian et al., 2013)	Proposes a workflow based on the integration of open BIM and open GIS in order to be effectively managed low-disturbance constructions by public administrations	
(Xu et al., 2014)	Proposes a City Information Modeling (CIM) notion that combines the useful features of BIM and GIS domains in order to properly manage urban areas	
(Boyes et al., 2017)	Studies how the transformation between Computer-Aided Design (CAD), IFC, and 3D GIS can be achieved for effective asset management in terms of the BIM usage that is stipulated by the administration	
(Hijazi et al., 2011)	Proposes a CityGML ADE, namely UtilityNetworkADE that enables the representation of the IFC entities related to utilities in CityGML models	
(Kang and Hong, 2015)	Develops a system architecture based on the Extract, Transform, and Load (ETL) method to benefit from the integration of BIM and GIS data in effective facility management	Integration
(Sun et al., 2020)	Implements a methodology that integrates the BIM models into 3D city models by benefiting from Airborne Laser Scanning (ALS) dataset	
(Uggla and Horemuz, 2018)	Compares these methods by benefiting from current IFC standard entities in terms of scale distortion, scale factor, angular distortion, and project height	
(Diakite and Zlatanova, 2020)	Proposes an approach that can automatically georeference the BIM models in a GIS environment with centimeter precision	
(Boyes et al., 2015)	Investigates the transfer of generated BIM models in Autodesk Revit into Oracle relational databases (RDBMS) as the IFC standard in order to use these models for different 3D GIS studies	
(Geiger et al., 2015)	Researches the generalization process between IFC and CityGML data	
(Hijazi et al., 2010)	Proposes an open-source GIS-based workflow that allows the visualization and query of IFC models within 3D GIS geoportal	
(Beetz et al., 2010)	Develops an open-source BIM platform based on IFC schemas in order to fill the deficiency of the model server in the AEC/FM sector	
(Karan et al., 2016)	Develops a framework based on semantic web technology that enables the data exchange and interoperability between BIM and	

	GIS domains in order to facilitate the construction supply chain management applications	

Table A.3. Publications, their proposed solutions, and related aspects in the paper in the sense of 3D registration of property ownership.

Publication	Proposed Solution	Aspect
(Kalogianni et al., 2020)	Reviews the 3D LASs in the context of the Spatial Development Lifecycle	Conceptual Framework
(Döner et al., 2010)	Investigates the applicability of 3D cadastre with a time component	
(Ayazli et al., 2011)	Develops a database with UML for 3D registration of property rights	
(Griffith-Charles and Sutherland, 2013)	Analyzes the transition to 3D cadastre in Trinidad and Tobago by considering costs and benefits and suggests specific regions for 3D registration of property ownership based on the results of the analysis	
(Dimopoulou and Elia, 2013)	Investigates the similarities, differences, and constraints in the legal codes of different jurisdictions to meet the needs for ensuring the registration of various legal spaces within 3D cadastre	
(Ho and Rajabifard, 2016)	Investigates the legal barriers for implementation of 3D cadastre	
(Kitsakis and Dimopoulou, 2014)	Investigates the legislations that contain the definition of ownership rights regarding 3D cadastre	
(Kitsakis et al., 2019)	Investigates the contribution of 3D modelling for management of public law requirements in the Australia, Victoria context	
(Kitsakis and Dimopoulou, 2020)	Investigates the impacts of 3D public law requirements	
(Paasch et al., 2016)	Examines the current legal issues regarding 3D cadastre	
(Kitsakis and Dimopoulou, 2017)	Investigates how public law requirements can be applied in 3D cadastre context	
(van Oosterom, 2013)	Examines the progress and remained challenges in the 3D cadastre context	
(Spirou-Sioula et al., 2013)	Proposes a system approach that facilitates the transition to 3D cadastre	
(Guo et al., 2013)	Develops a porotype for 3D cadastre in Shenzhen, China	
(Paulsson, 2013)	Investigates the reasons on why 3D cadastre should be included in a legal system	
(Paulsson and Paasch, 2013)	Examines the current state in 3D cadastre based on legal, technical, registration, and organizational perspectives	
(Jazayeri et al., 2014)	Investigates the appropriate data sources for 3D cadastre	
(Siejka et al., 2014)	Researches transition to 3D cadastre in Poland by taking CAD, GIS, and DBMS into account	

(Shojaei et al., 2015)	Proposes and evaluates a 3D visualization prototype for 3D cadastre	
(Shojaei et al., 2018)	Proposes a web-based application prototype for 3D cadastre	
(Çoruhlu et al., 2016)	Investigates the 3D registration of property rights pertaining to cultural heritage	
(Ho and Rajabifard, 2016)	Examines the usability of BIM for 3D land administration in Singapore	
(Shojaei et al., 2016)	Examines the challenges in ePlan for the 3D modelling of subdivision plans	
(Drobež et al., 2017)	Investigates the usability of current cadastral data for 3D cadastre transition	
(Vučić et al., 2017)	Proposes a 3D Multipurpose LAS to enable the 3D cadastral system in Croatia	
(Višnjevac et al., 2017)	Examines the usability of NoSQL database for 3D cadastre	
(Višnjevac et al., 2019)	Proposes a web application prototype based on NoSQL database and JavaScript library for 3D cadastre	
(Gulliver et al., 2017)	Investigates the appropriate way for the transition to 3D digital cadastre	
(Jaljolie et al., 2018)	Examines the need for an update of current legislative documents regarding 3D cadastre in Israel context	
(Bydłosz et al., 2018)	Suggests the use of spatial planning objects within the 3D cadastral data model	
(Olfat et al., 2018)	Examines the surveying industry in Victoria, Australia within the 3D cadastre context	
(Gkeli et al., 2019)	Proposes an application for acquisition and modelling of crowdsourced data in 3D cadastre context	
(Griffith-Charles and Sutherland, 2020)	Examines the usability of LIDAR dataset for 3D cadastre in low-income countries	
(Ghawana et al., 2020)	Suggests the raising of the awareness of public and relevant institutions for the transition to 3D cadastre in the context of Delhi, India	
(Isikdag et al., 2015)	Investigates the current state of usability of 3D models from land valuation perspective within 3D cadastre	
(Loshi, 2018)	Examines the project that aims to transition from 2D drawing-based system into 3D digital data-based cadastre system within Pristina, Kosovo	
(Larsson et al., 2020)	Examines the remained challenges for 3D digital cadastre transition in the Sweden context	
(Kim et al., 2015)	Proposes a methodology that is composed of obtaining a detailed point cloud of the underground structure by using laser scanning, creating the as-built BIM model, and representing the physical objects related to the 3D cadastre	
(Drobež et al., 2016)	Researches the usability of remotely-sensed images as a source for 3D cadastral data in Slovenia	
(Rajabifard et al., 2018)	Investigates whether the current 3D spatial data models meet the requirements for handling of legal interests in terms of specific administration regulations within Victoria, Australia.	
(Floros et al., 2017)	Researches the 3D building modeling based on the SketchUp software for the land administration paradigm	
(Karki et al., 2013)	Develops validation rules for 3D registration of property ownership	Modelling Guidelines

(Navratil and Unger, 2013)	Investigates the usability of different height systems for 3D cadastre and noted that there is no system that fits all countries	
(Wang et al., 2017)	Examines the usability of visualization transparency in 3D cadastre context	
(Ying et al., 2019)	Develops an algorithm that improves the visualization of 3D objects that can be used for the representation of 3D property units	
(Shi et al., 2019)	Proposes an algorithm based on conformal geometric algebra for conducting topological analysis in 3D cadastre context	
(Zhang et al., 2019)	Proposes a computation framework based on CGA in 3D cadastral data model context	
(Zhang et al., 2016)	Proposes a 3D cadastral model based on CGA	
(Knoth et al., 2020)	Proposes a new framework that enables the updating of 3D digital cadastre databases by exploiting solid models	
(Tekavec and Lisec, 2020a)	Examines the usability of SFCGAL 3D functions for data extraction from 3D cadastral and BIM data	
(Soon, 2013)	Proposes a Web Ontology Language (OWL) based approach that enables the representation of user roles in land administration processes such as registration of land titles and submission of survey plans	
(Stoter et al., 2013)	Creates an extension to LADM for the transition to 3D cadastre in Holland	The Use of Standards
(Pouliot et al., 2013)	Carries out a comparative analysis that contains the 3D registration of condominiums in keeping with LADM in France and Canada	
(Li et al., 2015)	Proposes a model based on Semantic Volume Texture (SVT) as an extension of CityGML for illustration purposes in the context of 3D cadastre	
(Lee et al., 2015)	Proposes a country profile of LADM is proposed for Korea	
(Janečka and Souček, 2017)	Proposes a country profile of LADM is proposed for the Czech Republic	
(Radulović et al., 2017)	Proposes a country profile of LADM is proposed for Serbia	
(Radulović et al., 2019)	Expands country profile of LADM for Serbia	
(Vučić et al., 2020)	Proposes an extension to LADM for 3D cadastre in Croatia	
(Alkan and Polat, 2017)	Proposes a country profile of LADM is proposed for Turkey	
(Kalogianni et al., 2017)	Proposes the integration of LADM and INTERLIS for 3D registration of property rights	
(Gkeli et al., 2020)	Proposes a technical solution based on crowdsources data and LADM for 3D cadastre	
(Olfat et al., 2019)	Proposes a BIM-based approach for registration of building subdivision in 3D cadastre context	
(Tekavec and Lisec, 2020b)	Proposes an approach providing to create IndoorGML datasets from 3D cadastral data	
(Cagdas, 2013)	Develops a CityGML ADE that enables the representation and management of legal and physical objects pertaining to tax payment of dwellings by taking laws related to property ownership in Turkey into consideration	

(Góźdź et al., 2014)	Proposes a CityGML ADE that makes possible the representation of physical and legal elements with regard to property ownership by means of LADM	
(Ying et al., 2014)	Suggests a framework that includes the conversion of CityGML building models into 3D property units as a means of simplifying and repairing those models	
(Rönsdorff et al., 2014)	Proposes a CityGML ADE that allows the modeling of the feature classes related to 3D cadastre within LADM	
(Soon et al., 2014)	Extends the previous research that offers the formalizing LADM structure by using OWL in order to integrate building modules of CityGML and hence to represent legal objects with their physical components in the context of 3D cadastre	
(Li et al., 2016)	Develops a CityGML ADE with the help of LADM in order to straightly delineate the legal rights with their physical components	
(Sun et al., 2019)	Proposes and exemplifies a framework that includes the integration of BIM and GIS models in the representation and visualization of the property rights	
(Sladić et al., 2020)	Proposes a process model based on IFC for 3D cadastre in Serbian	
(Cemellini et al., 2020)	Develops a 3D cadastre prototype that is web-based and compatible with LADM	
(El-Mekawy and Östman, 2012)	Investigates whether UBM can be efficiently used for 3D cadastre studies	
(El-Mekawy et al., 2014)	Examines the BIM-based approach for 3D cadastre	
(Atazadeh et al., 2017d)	Examines the qualities of various BIM models, especially IFC open-data standard, as legal, physical, and integrated in terms of frame rate, query speed, and communication of structural boundaries for recording 3D ownership interests	
(Atazadeh et al., 2016)	Develops a BIM-based prototype that beneficially allows the depiction of 3D property ownership rights	
(Oldfield et al., 2016)	Investigates how BIM models in IFC open-data format can be used as an input for registering legal interests into cadastral databases	
(Oldfield et al., 2017)	Proposes an approach that integrates and maps the IFC and LADM	
(Atazadeh et al., 2017b)	Proposes an extended IFC schema that allows the representation and visualization of legal rights as 3D digital data towards multi-landlordism	
(Atazadeh et al., 2017c)	Examines how the BIM-based approach can overcome the problems that stem from the use of 2D subdivision plans	
(Atazadeh et al., 2017a)	Proposes an IFC-based modeling approach for representing and perception of proprietary rights with respect to complex buildings	
(Atazadeh et al., 2018b)	Proposes a BIM-based approach that efficiently enables the description of common property within real estate that has multiple owners as a means of manipulating IFC data types	
(Atazadeh et al., 2018a)	Researches how LADM and IFC can be combined to integrate the legal and physical objects in the context of 3D cadastre	
(Andrée et al., 2018)	Examines the usability of BIM data for 3D representation of cadastral data	
(Barzegar et al., 2020)	Proposes a BIM-based spatial query approach in order to address the failures in the obtaining of attribute information	

	associated with the physical representation of legal rights in complex buildings	
(Atazadeh et al., 2019)	Studies how information related to legal rights in buildings can be obtained from 3D BIM models to support cadastre applications	
(Aien et al., 2013b)	Proposes a 3D cadastral data model	
(Aien et al., 2013a)	Proposes a 3D cadastral data model	
(Aien et al., 2015)	Proposes a 3D cadastral data model	
(Thompson et al., 2017)	Expands on how land parcels in survey plans can be represented as 3D multi topologic objects for land administration applications using LandXML	
(Stoter et al., 2017)	Investigates how the legal rights of new structures can be registered to cadastre as 3D	
(Alattas et al., 2017)	Investigates whether the integration of IndoorGML and LADM can offer noteworthy results for indoor navigation applications that are taken RRRs into consideration	
(Shin et al., 2020)	Extends the IFC schema to prevent misunderstanding on property ownership in multifaceted buildings	
(Eriksson et al., 2021)	Proposes the use of Git for versioning of buildings and planning within 3D cadastre	
(Alkan et al., 2021)	Develops a model based on LADM for 3D registration of property rights	
(Ying et al., 2017)	Develops an algorithm that enables the creation of 3D volumetric objects, which can be used within a 3D cadastral database, by using CityGML LOD3 building elements	

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