BIM-based 3D Cadastral Management

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SMART BUILT ENVIRONMENT

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KTH VETENSKAP OCH KONST
LUNDS UNIVERSITET
HÖGSKOLAN I GÄVLE
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Sammanfattning

För 3D-fastighetsförvaltning är huvudsyftet förmågan att utveckla och hantera 3D-fastighetsförvaltning digitalt, holistiskt och hållbart. För att uppnå det har projektet BIM-baserad hantering av 3D-fastighetsinformation haft huvudfokus på hur man kan använda en BIM-ansats i digitaliseringen av 3D-fastighetsinformation genom en tvärvetenskaplig metodik. Forskargruppen har bestått av forskare från KTH, Lunds universitet, Högskolan i Gävle och Lantmäteriet samt arbete tillsammans med en referensgrupp från Stockholms stad och industriföretag.

I projektet har två arbetspaket genomförts: Arbetspaket 1 –livscykel för en svensk 3D-fastighetsbildningsprocess och Arbetspaket 2 – fastighetsekosystem. Arbetspaket 1 har utvecklat en BIM-baserad livscykel för en svensk 3D-fastighetsbildningsprocess i form av en IDM-processkarta för att visa hur 3D-fastighetsdata, 2D/3D GIS-data och BIM-modeller skulle kunna delas, utbytas och lagras genom hantering av olika aktörer. Arbetspaket 2 har föreslagit och skapat ett nytt multidisciplinärt nätverk för samarbete–affärsekosystembaserad fastighetsförvaltning och utvidgning till ett bredare ramverk – fastighetsekosystem, som skulle kunna länka *policy*, *aktörer*, *process*, *teknik* och *affärer* tillsammans för en bättre och djupare förståelse av hållbar 3D-fastighetsförvaltning ur juridiska, tekniska, registrerings- och organisatoriska perspektiv.

Sammantaget visar resultaten att integrationen av BIM och 3D GIS för 3D-registrering kan ge involverade aktörer nödvändig och korrekt information, kunskap och insikt som förbättrar ekonomiska, miljömässiga och sociala resultat på ett hållbart sätt för både städer och medborgare. Vidare skulle fastighetsekosystemet kunna underlätta policyimplementering, samordna aktörers samarbete, förbättra processeffektiviteten, uppnå teknikintegration och innovation samt skapa värde över multidisciplinära kompletterande bidrag. I slutändan ger författarna rekommendationer från policy-, aktörs-, process-, teknik- och affärsaspekter som på ett holistiskt sätt skulle kunna underlätta digitaliseringen av livscykeln för 3D-fastighetsförvaltning och påskynda utvecklingen av fastighetsekosystemet på ett hållbart sätt.

Målgruppen för resultatet av detta projekt är alla som deltar i eller berörs av 3D-fastighetsbildning, både vid nybyggnation och inom befintligt byggnadsbestånd, såsom kommunala och statliga förvaltare, exploatörer, sökande/fastighetsägare, medborgare, politiker, myndigheter och andra organisationer.

Summary

For 3D cadastral management, the major purpose is the ability of developing and managing 3D cadastre digitally, holistically and sustainably. To achieve that, the project BIM-based 3D cadastral management has had a main focus on how to use a BIM approach in the digitalization of 3D cadastral management through an interdisciplinary methodology. The research team has consisted of researchers from KTH, Lund University, Universityof Gävle and Lantmäteriet, as well as collaboration with a reference group from the City of Stockholm and industry companies.

In the project, two work packages have been carried out: Work Package 1 – lifecycle of the Swedish 3D property formation process and Work Package 2 – cadastre ecosystem. The WP1 has developed a BIM-based lifecycle of the Swedish 3D real property formation process in the IDM process map to fill in the gap of how relative 3D cadastral data, 2D/3D GIS data and BIM models could be shared, exchanged and stored through activities between different actors. The WP2 has proposed and built a new multidiscplinary collaboration network – Business ecosystem-based cadastral management and expanding to a wider framework – Cadastre ecosystem, which could link the pillars *policy*, *actors*, *process*, *technology* and *business* together for a better and deeper understanding of sustainable 3D cadastral management from legal, technical, registration and organizational perspectives.

Overall, the findings show that the integration of BIM and 3D GIS for 3D cadastre can provide involved actors with necessary and accurate information, knowledge and insight that enhances financial, environmental, and social outcomes sustainably for both cities and citizens. Furthermore, the cadastre ecosystem has abilities to facilitate policy implementation, coordinate actors' collaboration, improve processes efficiency, achieve technology integration and innovation and create value across multidisciplinary complementary contributions. In the end, the authors provide recommendations from policy, actors, process, technology and business aspects that would holistically facilitate the digitalization of the lifecycle 3D cadastral management and accelerate the development of the cadastral ecosystem sustainably.

The target group / stakeholders for the result of this project would be everyone participating in or being affected by 3D property formation, both in new construction and within the existing building stock, such as municipal and state administrators, applicants / property owners, developers, citizens, politicians, authorities and other organizations.

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1 Introduction

1.1 Background

Traditionally, a cadastre is normally a 2D parcel based, and up-to-date land information system containing property unit information (e.g. rights, restrictions and responsibilities). One of the triggers of the Smart Built Environment program is that data should be shared between the planning, design, construction and management phases in the built environment processes as an unbroken flow of information. 3D cadastre is an important use case that both need and could contribute to an unbroken digital chain of data that spans a building's lifecycle, from planning, to development, construction, use and facility management, and demolition and recycling.

For 3D cadastral management, the major purposeis the ability of developing and managing 3D cadastre digitally, holistically and sustainably. One of the most important fuctions of digitalization is the ability of digital data to be used over phases in the lifecycle of the built environment. However, the current state of 3D cadastral management is that there are 3D property rights that have been formed in a few projects, but they are still formed and registered with a 2D cadastral index map and land register (Andrée et al., 2018; Larsson et al., 2020). Within the 3D property formation process, the main and practical difficulties are when, what and how cadastral data should/will be exchanged and stored from/to whom (organizations/actors).

Meanwhile, Building Information Modelling (BIM) has prominently innovated and digitalized the building environment through digital representation of buildings, lifecycle process and management for involved actors. In terms of 3D cadastre, BIM provides powerful abilities from legal, technical and registration process perspectives (more details see Section 2.2).

Therefore, in the endeavor to exploit benefits of digitalization, this project ties the cadastral legal data together with digital building data to generate a BIM-based lifecycle 3D property formation process. According to the research results of BIM-based 3D cadastral management, we further propose a conceptual framework that is conductive for the organizational cadastral management based on a business ecosystem, as well as expand it to a wider definition – cadastre ecosystem.

This project entitled "*BIM-based 3D cadastral management*" (swe: *BIM-baserad hantering av 3D-fastighetsinformation*), is a continuation project from the Smart Built Environment research platform project "Data Quality and Data Responsibility within the Built Environment". It is linked to the Smart Built Environment impact targets: *Improved uninterrupted flow of information in the building and planning process* and *Increased integration of BIM and GIS*.

1.2 The project: BIM-based 3D Cadastral Management

The introduction of 3D property in Sweden has been a tool to increase the possibilities of constructing and financing often large and more complex facilities, creating more secure and clear ways of constructing e.g. infrastructure objects, as well as facilitating the management of this property (Paulsson, 2013). Moreover, better management of data and more information on 3D cadastre will reduce the risk of errors in the processes.

The project called “BIM-based 3D cadastral management” was established to perform 3D cadastral management research to contribute to an investigation of these issues considering efficiency and providing recommendations for different stakeholders including authorities and required changes to policies and technical processes which will be necessary, given a future unbroken digital information flow and optimal organizational 3D cadastral management. That has been the main focus of the project.

The project was initially established as a two-year project, including two work packages WP 1 and WP 2. WP 1 and WP 2 have been carried out and completed. Outcomes include a doctoral thesis, two manuscripts submitted to international scientific journals, one published peer-reviewed international conference paper (best paper awarded) and one presentation in a national conference.

The results of the project BIM-based 3D cadastral management could contribute primarily to shorten time and reduce the overall costs through an unambigous process and clear data exchange flow, and then, as a consequence thereof, contribute to the reduction of the environmental impact of the built environment sector. With an increased focus on 3D cadastral management throughout the lifecycle, a better basis is also provided for subsequent development of new opportunities and business models within the built environment.

1.3 Aim and objectives

To fill the gap, the project aimed to develop and evaluate methods to manage 3D cadastre from legal, technical, registration and organizational perspectives. There are currently shortcomings in both registration and visualization of 3D property units (since it is based on textual descriptions and 2D maps), which need to be resolved. A key issue to resolve these shortcomings is the sharing of digital information.

In this project, we aimed to develop a BIM-based lifecycle process that describes which information that needs to be transferred between the stakeholders and how this information is linked to the information model standards used. The project also aimed to study what motivates the stakeholders to share information.

1.4 Scope of the report

The scope of the report is relatively wide including cadastre, cadastral management, BIM, 3D GIS, business ecosystem and cadastre ecosystem. Each topic could be expanded into a complex domain, thus researched separately and deeply. Although the work in this report is nowhere near exhaustive regarding either, it provides a method for a multidisciplinary integration of BIM, 3D GIS and cadastre from data quality, lifecycle process, and cadastre ecosystem perspectives. The value of integrating these topics is to fulfil the demands of sustainable urban development and lifecycle management of 3D cadastre in the digitalization of cadastre and smart city based on BIM.

1.5 Sustainability

The methods used in the project mainly focused on BIM, 3D GIS, 3D cadastre and business ecosystem, with their aims are to improve quality, collaboration and efficiency for 3D cadastre in the lifecycle phases. Thus, this project contributes towards the following Sustainable Development Goals (SDGs) established in 2015 by the UN:

- **Goal 8** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- **Goal 9** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- **Goal 11** Make cities and human settlements inclusive, safe, resilient and sustainable
- **Goal 13** Take urgent action to combat climate change and its impacts

1.6 Organizations and outcomes

1.6.1 Project team

The research team consists of researchers from KTH, Lund University, University of Gävle and Lantmäteriet:

- Jenny Paulsson, KTH
- Jing Sun, KTH
- Kent Eriksson, KTH
- Lars Harrie, Lund University
- Jesper Paasch, University of Gävle and Lantmäteriet
- Väino Tarandi, V Tarandi AB

The project leader has been Associate Professor Jenny Paulsson, Department of Real Estate and Construction Management, KTH Royal Institute of Technology. From the department, Dr. Jing Sun has participated and carried out the main part of the project. Professor Kent Eriksson has taken active part of the project and has been the main supervisor of Jing Sun. Associate Professor Jenny Paulsson and Professor Lars Harrie have taken active parts of the project and were the co-supervisors of Jing Sun. Professor Jesper Paasch have participated in the research. Professor Väino Tarandi (retired now) has taken active part of the project and was co-supervisor of Jing Sun.

1.6.2 Reference group

The external reference group consists of construction firms, real estate firms, Lantmäteriet and Stockholms stad:

- Martin Andrée, Västra Gästriklands samhällsbyggnadsförvaltning
- Torbjörn Glad, JM
- Karolina Larsson, KLM Stockholms stad
- Fanny Nordqvist Darell, Stockholms stad
- Johan Norrsell, Svefa
- Linda Sabel, Lantmäteriet

1.6.3 Outcomes

Within the project, collaboration and dissemination of results have been carried out in the following:

- A PhD thesis has been completed and sucessfully defended by Jing Sun;
- One peer-reviewed conference paper has been presented in the international conference and published, which is also awarded *Best Paper of 3D GeoInfo & Cadastres 2021*:
    - Sun, J., Paasch, J., Paulsson, J., Tarandi, V., & Harrie, L. (2021). Towards Design and Development of a BIM-based 3D Property Formation Process. In Kalogianni, E., Abdul Rahman, A. & van Oosterom, P. (Eds.) *Proceedings of the 7th International Workshop on 3D Cadastres*, 11-13 October 2021, New York, USA, International Federation of Surveyors (FIG), Copenhagen, Denmark, pp. 405-419. https://doi.org/10.4233/uuid:4aa9343f-b965-4c44-ba0d-9f91142dc078.
- Two original papers have been submitted to an international scientific journal:
    - Sun J., Paasch J., Paulsson J., Tarandi V., & Harrie L. (2022). A BIM-based approach to design and development 3D property formation process - a Swedish case study. *Land Use Policy*. Under Review.
    - Sun J., Vigren O., Eriksson K., & Paulsson J. (2022). A Business Ecosystem-based 3D Cadastral Management and Cadastre Ecosystem. Submitted to *Land Use Policy*.
- Participation and presentation in a national conference

1.7 Disposition of the report

The report is based on and written as a compilation of the publications consisting of doctoral thesis, one published conference paper and two submitted international journal papers.

The report is structured into five sections:

- Section 1 consists of the background and introduction;
- Section 2 describes the related work including 3D cadastre and 3D cadastral management, BIM with three standards IFC, IDM and LOIN, business ecosystem, as well as linkages with previous projects in the Smart Built Environment;
- Section 3 and 4 introduce the two work packages with motivations, methods, results, findings and limitations, respectively;
- Finally, the report wraps up with concluding remarks in Section 5.

2 Background and related work

In this chapter, we provide a description of related work as a background to the two work packages.

2.1 3D Cadastre

In this section, we start with the introduction of traditional 2D cadastre and 2D cadastral management, and then describe the current situation of 3D cadastre and 3D cadastral management.

2.1.1 2D cadastre and 2D cadastral management

2D cadastre is normally a parcel based and an up-to-date land information system (FIG, 1995), defining cadastral boundaries in a 2D cadastral map and registering cadastral information in cadastral dossiers with development from paper-based to digital documentation that is often pdf-based.

The cadastre plays an essential role in the regulation of land use, that is usually managed by government agencies to record land parcels as a land information system containing a record of interests in land (e.g. rights, restrictions and responsibilities (RRRs)) for social and economic development (FIG, 1995). The cadastre provides both legal and spatial information for public land administration that is recorded in the cadastral documents or cadastral dossiers. Traditionally, most countries register legal information in the textual files and geographical information in cadastral maps. In cadastral dossiers, geodetic surveying methods are used for cadastral surveying and geodata in order to describe the boundaries of parcels, coordination and reference system in index maps. However, due to pressure on urban land for dwelling, structures of modern buildings have become more complicated both above and underground (Atazadeh et al., 2017). Traditional 2D cadastre cannot fully satisfy the needs of the property units, boundaries and space usages of complex buildings (Shojaei et al., 2013; Alattas et al., 2021). Therefore, it is imperative to address and avoid ambiguous problems by transiting 2D cadastre to 3D cadastre, as well as considering 3D cadastral management.

2.1.2 3D cadastre and 3D cadastral management

2.1.2.1 3D cadastre

3D property units can be defined as closed 3D volumes bounded both horizontally and vertically. The reason for introducing 3D cadastre is to enhance the possibilities of constructing and financing often large and more complex facilities, create more secure and clear ways of constructing e.g. infrastructure objects, as well as facilitate the management of this property (Paulsson, 2013; Andrée et al., 2018). To make efficient use of, foremost urban, space, several countries have introduced 3D cadastre such as Australia, Sweden, Malaysia, the Netherlands, Israel, and Poland (van Oosterom et al., 2018).

With the help of the 3D spatial technologies BIM and 3D GIS, 3D cadastre has given rise of increasing interests over the last decade (van Oosterom, 2013; El–Mekawy et al., 2014; Li et al., 2016; Oldfield et al., 2017; Atazadeh et al., 2017; Paasch and Paulsson, 2021). 3D representation and visualization of property units and property boundaries plays an essential role. One optimal way currently is to create an IFC-based cadastral model and then convert it to CityGML for representing as 3D cadastral index map and storing it in a database environment for example 3D City Database (3DCityDB, an open source database for CityGML, https://www.3dcitydb.org/3dcitydb/). This kind of implementation can be done by utilizing an Extract Transform and Load (ETL) tool, mostly via the data integration platform FME (https://www.safe.com/). In BIM/IFC models, *Spaces/IfcSpace* and *Zones/IfcZone* are the generally used functionalities to visualize logical spaces in the cadastral documents. Therefore, 3D cadastre is possible to better handle and manage both legal and spatial information of complicated buildings and infrastructure installations such as tunnels and other sub-surface constructions (Andrée et al., 2018; van Oosterom et al., 2018).

2.1.2.2 3D cadastral management

With the increased interest and demand in 3D property, 3D property formation has shown significance (Choon and Hussin, 2012; Andrée et al., 2018; Larsson et al., 2020) and it has been shown that 3D property formation is an effective method for subdividing and separating the ownership of different activities in densely-built areas, e.g. in cities (van Oosterom et al., 2018).

Challenges of cadastre management relate to the diversity of topics that need to be simultaneously taken into account in the formation of the agenda including organizations, legislation, users and user requirements, coordination of reference and height systems, data standards and geometry (Sun et al., 2019). 3D cadastre would be possible to connect digital data from all building lifecycle phases through different processes, for example 3D property formation process with initiation, preparation, decision, registration, and update phases. For that, BIM, GIS and legal data should be collected, exchanged and shared consistently across the sustainable management.

Moreover, 3D cadastre involves more stakeholders such as municipality, land surveyors, architects, contractors, owners, and property management companies. The relationships between different stakeholders have shown to be significant and complex to coordinate and collaborate. However, there is lack of studies to describe a digital process including data exchanges between the different actors based on this 3D digital model approach.

It also should be realized that 3D cadastre depends, to a great extent, also on user needs and business market, which are the motivation to build 3D cadastral models and apply those models in the sustainable cadastral management. Therefore, besides issues of integrated technology, 3D cadastre needs to be managed from social and organizational perspectives as well.

2.1.3 Land Administration Domain Model (LADM) – legal models

The Land Administration Domain Model (LADM) as an international standard for land administration (Edition I, ISO 19152: 2012) has been used widely around the world and lays the foundation for progressive development and enhancement of current land administration systems (van Oosterom and Lemmen, 2015; Atazadeh et al., 2017). It is defined as a knowledge domain specific standard that provides a shared ontology, defining a common terminology for land administration (Lemmen et al., 2021). With the increasing need of managing 3D cadastral information, the LADM plays an essential role to digitalize cadastral management, where the legal information model is often stored in accordance with. The LADM is treated as a conceptual model that indicates which data entities are included and how they are related to each other (Kalantari et al., 2015). It supports registration of legal information as well as the increasing use of 3D representations of spatial units without putting an additional burden on the existing 2D representations (ISO, 2012; Góźdź et al., 2014; Paulsson and Paasch, 2015; Vučić et al., 2017).

The LADM Edition I is organized into three UML main packages namely *Party Package*, *Administrative Package*, *Spatial Unit Package* (and one sub package of Spatial Unit Package: *Surveying and Representation Package*) (ISO, 2012). For these packages, there are four basic classes: *LA_Party*, *LA_RRR*, *LA_BAUnit*, and *LA_SpatialUnit*, shown in Figure 1.

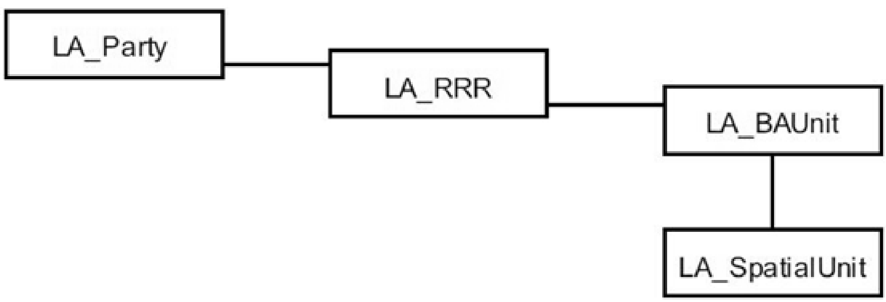


Figure 1. LADM basic classes (ISO, 2012).

- *LA_Party* is the main class of the Party Package, which defines the actors such as people or organizations in the land administration (associated to *LA_RRR*).
- LA_RRR is one main class of the Administrative Package as an abstract class for modelling various types of rights, restrictions, and responsibilities with three specialization classes: *LA_Right*, *LA_Restriction*, and *LA_Responsibility*.
- *LA_BAUnit* is the other one main class of the Administrative Package as a basic administrative unit to register 'basic property units' that allows a combination of spatial units (e.g. an apartment and a parking place from different levels as one unit) (associated with the same *LA_RRR*).
- *LA_SpatialUnit* is the main class of the Spatial Unit Package with two refined specializations concern legal spaces but do not necessarily coincide with the physical spaces *LA_LegalSpaceBuildingUnit* for building units and *LA_LegalSpaceUtilityNetwork* for utility networks, which provides various spatial representations of ownership interests (e.g., areal and volumetric 3D objects) (Janečka and Souček, 2017).

The LADM Edition I can improve the 3D cadastre by facilitating understanding from legal perspective or as a legal database when registering 3D property units and integrating with spatial technologies BIM and 3D GIS (van Oosterom and Lemmen, 2015; Alattas et al., 2021; Ying et al., 2021).

In order to better refine and cover land administration functions, the revision of LADM - LADM Edition II is currently under development and will be published as multiple coherent packages with every part in separate standard: Fundamentals; Land Registration; Marine Space Georegulation; Valuation Information; Spatial Plan Information; and Implementations. The LADM Edition II will be addressing current and future land administration challenges, adopting a lifecycle approach, and going beyond a conceptual model (Lemmen et al., 2021; Polat et al., 2022). However, this repot only utilizes the current standard LADM Edition I.

2.1.4 Integration of BIM and 3D GIS with cadastre

For 3D cadastral visualization, there are two common integration ways to generate 3D cadastral models, direct or indirect.

1) Direct way: is to directly extract heights of different spatial units based on the description in cadastral documents including the 2D index map and architectural drawings, which 3D property units and property boundaries can be modelled in CityGML or in BIM/IFC. However, the biggest problem is that it does not consider the actual properties of building elements and their interlinked relationships, for instance

property boundaries changing from exterior walls to interior walls. Which means, the property boundaries cannot be identified clearly and represented accurately. Major geometric errors and indiscriminate property management will occur in reality.

2) Indirect way: is to link cadastral information as legal model to physical model. For instance, BIM with detailed description of building elements could be used to define 3D cadastral boundaries accurately and generate 3D cadastral models linking with cadastral information. To visualize 3D cadastre on city level and further analysis, single BIM-based cadastral model could be converted into CityGML, and further to create 3D cadastral index maps integrated with city models in large scale. However, it must be stressed that cadastre has no data maturity level. To digitalize cadastral management, cadastre utilized LADM to create a legal model and BIM/3D GIS for physical models.

Currently, the integration of BIM and 3D GIS (sometimes denoted GeoBIM) for modelling 3D buildings is quite popular especially at the data level by converting IFC data to CityGML (Olsson et al., 2018; Noardo et al., 2020; Biljecki et al., 2021). Most transformation and conversion for different spatial data (especially 2D/3D GIS data, BIM and CAD) are adopted by the data integration platform FME (the Feature Manipulation Engine, developed by Safe Software) as an ETL (Extract, Transform, and Load) and integration tool.

When integrating BIM, GIS and cadastral information, an issue should be aware that information will evolve and be used for multiple purposes and by different actors during its lifecycle (Eriksson et al., 2021). Therefore, collaboration is the key point for involved actors from different sectors. Besides, version management is an optimal way to avoid ambiguous problems when different actors are sharing, exchanging and storing 3D cadastral models.

2.2 BIM – Building Information Modelling

In this section we focus on the BIM background, definition, integrated application and standards; these standard are created by consensus and approved by international technical groups working within the ISO framework.

Nowadays, for many countries, BIM has been developed to digitalize construction across the entire lifecycle of a built project. BIM is a digital representation of a building in the lifecycle phases from design through construction to operation and maintenance (Eastman et al., 2011). The concept of BIM can be understood as being composed of two parts: building information models and building information modelling. In the Architecture, Engineering and Construction (AEC) industry, BIM models contains rich details of building properties geometrically and semantically such as structures, elements, spaces, schedules, and other aspects of a construction project. BIM models could be classified into two file formats, proprietary data created by software manufacturers and non-proprietary data that is vendor-neutral and can be read and edited by any type of software, for example the international open standard IFC (see Section 2.2.1) (Eastman et al., 2011; Borrmann et al., 2018; buildingSMART, 2019).

Meanwhile, BIM is also a process to design, create, exchange, coordinate, operate and manage building information through the lifecycle project phases for all involved actors (Borrmann et al., 2018). The IDM is an open BIM process standard that captures and specifies information flow (see Section 2.2.2). The BIM can extend throughout the whole building development lifecycle and provide comprehensive functions for stakeholders (e.g. owners, managers, designers, engineers and contractors). It supports building lifecycle management such as construction, project, cost management as well as facility operation (Eastman et al., 2011). Furthermore, in terms of 3D cadastre, BIM provides powerful abilities from legal, technical and registration process perspectives (more details see Section 3) .

To improve communication and interoperability, the buildingSMART alliance has developed international open BIM standards for the building industry worldwide, such as IFC, IFD (International Framework for Dictionaries) and IDM/MVD (Model View Definitions) (buildingSMART, 2019). The buildingSMART Data Dictionary (bSDD) mandates to instead IFD and is an online service that hosts classifications and their properties, allowed values, units and translations (ISO 19650-1). MVD can be generated automatically by linking IDM and bSDD that allows linking between all the content inside the database (ISO 19650-1). Figure 2 shows the basic relationships of these three standards that bSDD (previously IFD) specifying the terminology; IFC enabling digital storage for interoperability; and IDM/MVD identifying and specifying the process.

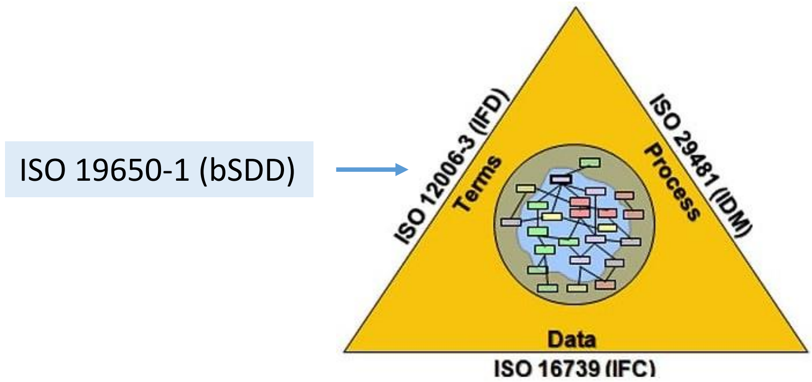


Figure 2. Open BIM standards: bSDD (previously IFD), IFC, IDM (adapted from buildingSMART, 2019).

2.2.1 Industry Foundation Classes (IFC) – physical models

As of today, IFC as the non-proprietary BIM data is most widely used to exchange and share information among software applications by many different stakeholders (Borrmann et al., 2018). IFC is an open international standard for BIM that defines building data elements and shows spatial relationships among its entities by IFC schema. It specifies EXPRESS schema as the source to generate XML schema (XSD) which can describe installation, construction and operation in a logical way.

As an object-oriented data model, IFC defines specialization and generalization relationships in the inheritance hierarchy (Borrmann et al., 2018). In the IFC inheritance hierarchy, all entities start from *IfcRoot* (as shown in Figure 3) that provides unique identification of an object by Globally Unique Identifier (GUID). *IfcObjectDefinition* as an abstract superclass represents physical, spatial objects and conceptual elements (e.g. building elements, spaces, processes, costs, etc.) (ISO, 2018). The class *IfcProduct* is an abstract class that represents spatial or physical context covered in subclasses *IfcSpatialStructureElement* that describes non-physical spatial objects (including subclasses *IfcSite*, *IfcBuilding*, *IfcBuilding-Storey* and *IfcSpace*) and *IfcElement* that describes physical objects (subclass *IfcBuildingElement* representing all building elements such as *IfcWall*, *IfcSlab*, *IfcWindow* etc.), respectively (ISO, 2018).

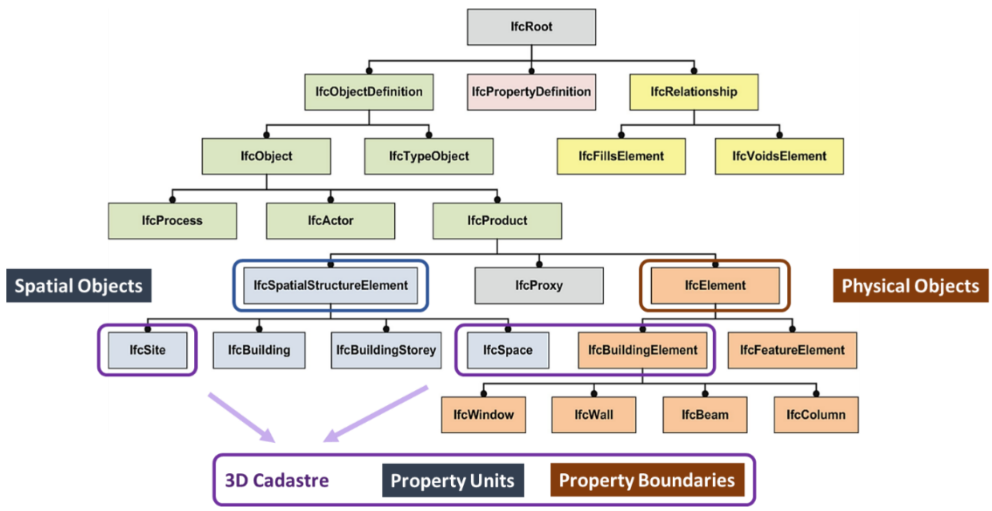


Figure 3. The IFC hierarchical structure and entities mostly integrated with 3D cadastre (adapted from Borrmann et al., 2018).

In view of the fact that IFC supports definition of building elements and the spatial relationships, BIM/IFC models have also been used as geometrical models to integrate with cadastral information as 3D cadastral models (Atazadeh et al., 2021; Einali et al., 2022). As shown in Figure 3, *IfcSpace* can represent cadastral property units in 3D and the classes of *IfcBuildingElement* can visualize legal property boundaries in 3D (see more details in Section 2.4.4). For instance, Atazadeh et al. (2017) explored the feasibility of BIM to model the boundaries of ownership spaces inside buildings and identified relevant geometric and semantic IFC entities using a case study.

2.2.2 Information Delivery Manual (IDM) – lifecycle process

The BuildingSMART introduced the IDM as an open process standard, which makes it possible to organize data exchange processes in a graphical notation and subsequently derive exchange requirements for data exchanges occurring in the process (Beetz et al., 2018). Simply to say, the IDM specifies *which information* is delivered by *whom*, *when*, to *whom*, and *how*. Considering the major benefits of IDM, several research studies have started to utilize the IDM process to describe how cadastral information is shared and exchanged between stakeholders in the 3D property formation procedure. Oldfield et al. (2017) proposed an IDM workflow for the Dutch cadastral registration and Sladić et al. (2020) identified user needs in IDM to model business processes.

The IDM is mainly composed of three parts: a process map (PM), exchange requirements, and a model view definition (MVD), where the necessary information for handovers between project participants is identified (Sacks et al., 2018). Figure 4 schematically depicts the overview of the IDM/MVD method used for the IFC based exchange of information in six steps (Beetz et al., 2018).

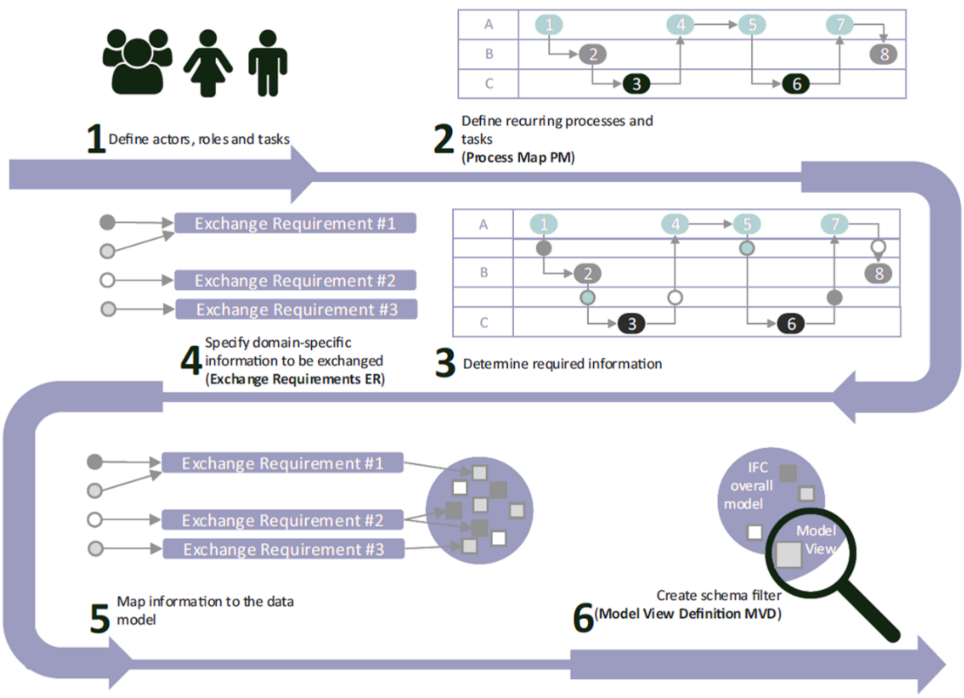


Figure 4. Framework of the IDM/MVD method used for the IFC based exchange of information (Beetz et al., 2018).

This research uses the first four steps of IDM method, which defines the actors, roles and tasks in 3D property formation process and designs a process map to illustrate the cadastral requirements exchanging between different actors (see an example in Figure 5).

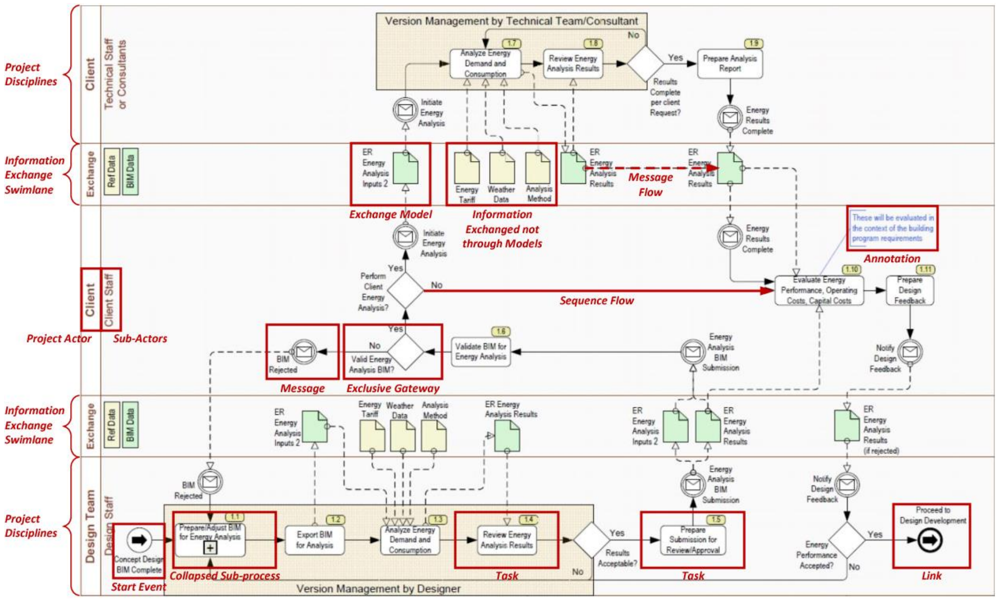


Figure 5. IDM process map (Hyun et al., 2016).

2.2.3 Level of Information Need (LOIN)

The level of information need, LOIN, provides methods for describing information to be shared according to exchange information requirements between actors. In relation to IDM, with the model view and the exchange requirements, LOIN defines the characteristics of the exchanged objects both as the requirements and the realized exchanged information. As a new European standard EN 17412-1, LOIN specifies the granularity of information exchanged in terms of geometrical information, alphanumerical information, and documentation, which should be used to specify the information delivery between actors, see Figure 6.

Each exchange of information must consider each recipient's needs and the purpose for supplying that information. LOIN can be seen as replacing the combination of Level of Detail (LoD) and Level of Information (LoI). In the delivery phase of projects/assets, the appointing party (project client) should consider the method of assignment for LOIN and what is required to meet each information requirement.

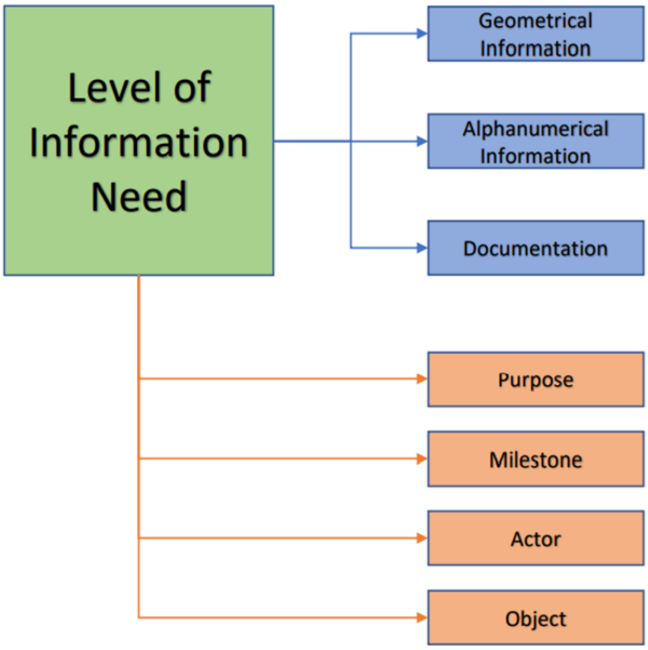


Figure 6. Characteristics of the exchanged object (CEN-CENELEC, 2019).

2.3 Business ecosystem

The business strategist Moore introduced the theory of business ecosystem and developed the concept in 1993. Business ecosystem that is evolved from biological ecosystem is the network of organizations and individuals involved in the products and services (see Figure 7) that are affected by each other through cooperation and competition (Moore, 2006; Mäkinen and Dedehayir, 2012;). Moreover, it is a collaboration to create a holistic, integrated technological system of complementary capabilities and companies (Kim, 2016; Jacobides et al., 2018; Ma et al., 2021). Interest in ecosystem thinking has grown significantly in recent decades, probably because firms, such as Google, Apple and Amazon, have been able to disrupt traditional industries by redefining value creation and capture mechanisms in their business ecosystems, and as incumbent actors face new complexities in their environments. Ecosystem concepts are also well suited to the study of more traditional operating environments, such as the built environment sector.

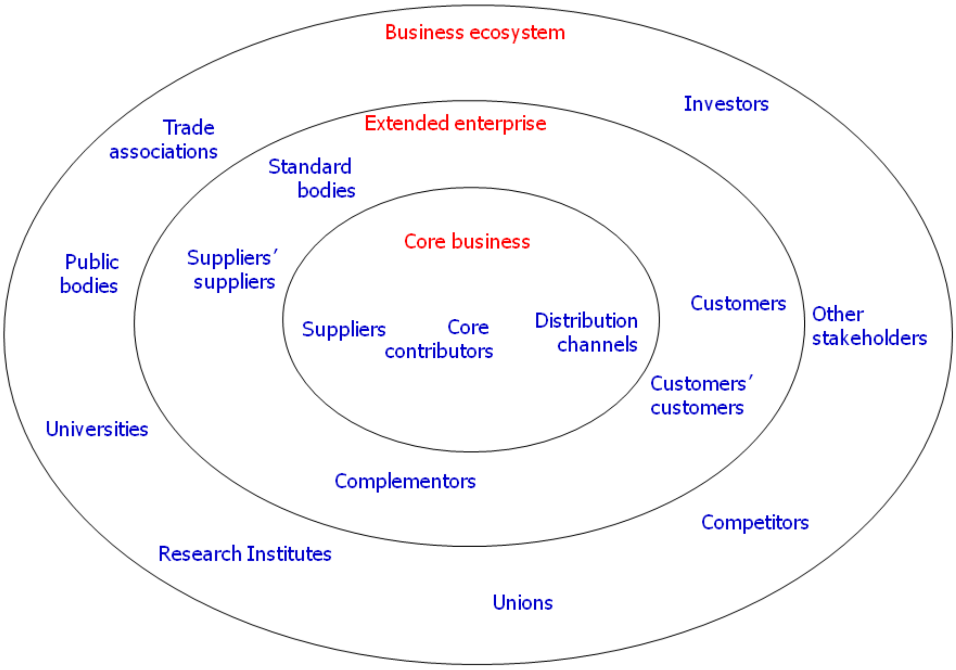


Figure 7. The layers of a business ecosystem, adapted from Moore's theory (Heikkilä and Kuivaniemi, 2012).

Recently, Eriksson et al. (2019) have re-defined business ecosystems as "systems of workflows that contribute toward a common system-level business goal". This definition emphasizes that ecosystem actors are interdependent of each other through workflows, and that they shape and are impacted by system-level goals. The advantage of this perspective is that it focuses on the business logics of multiple actors (Moore, 1993), complementarities between organizations that engage in business and innovation (Jacobides et al., 2018), and system-level characteristics of business and innovation (Eriksson et al., 2019). Moreover, the business ecosystem concept draws from ecological and life cycle perspectives and it is not restricted, for example, by the boundaries of firms, industries, technologies, or institutions. Legenvre et al. (2022) analyzed that business ecosystem is best suited for dynamic business environments with complex and evolving technical systems.

From organizational perspectives, actors in a business ecosystem are motivated to collaborate to develop and expand existing and new markets (Moore, 2006). Eriksson et al. (2019) analyzed actors' role and value, as well as how different actors contributed to shipping and logistics ecosystem in different phases of vessel life cycle. Iversen et al. (2022) used Q-methodology to understand and identify the range of stakeholder perspectives and provided evidence to show that stakeholder conflict was a significant barrier to woodland creation in upland areas, which was important to engage with stakeholders with understanding, participation and collaboration.

Corresponding to an ecosystem, developing a strategy to match the environment is essential (Iansiti and Levien, 2004). The authors suggested undertaking and performing strategic analysis throughout the lifecycle because strategic interdependencies across multiple organizations span multiple industries. After decades in unprecedented growth of integrated technologies, urban ecosystem and smart city ecosystem provide large help in curtailing the environmental hazards by means of applying environment friendly and cost-effective techniques (Ahad et al., 2020). Thus, implementing business ecosystems to manage stakeholders of 3D cadastral management could increase local economic growth through new methods of dynamic business interactions and global cooperation between cadastre and business communities.

2.4 Linkages to other projects

This *BIM-based 3D Cadastral Management* project is a continuation of the previous project *Data Quality and Data Responsibility within the Built Environment* within the Smart Built Environment research platform (https://smartbuilt.se/projekt/kunskap-ochkompetens/forskningsteam/), which links to several other related projects:

- *DigSam –digital community-building process*: studied legal aspects of storage of 3D Geodata / BIM models and identified legal barriers that slow down digitalization such as filing issues, quality deficiencies in digital information and lack of cooperation between the different actors (Andreé et al., 2019).
- *Delivery Specifications for Geodata-BIM*: developed and tested delivery specifications for Geodata and BIM in the building permit process, as well as a proposal for a new Swedish standard for building models in 2D and 3D that comply with CityGML's regulations (Neland et al., 2019).
- *Smart Planering för Byggande*: seeked possibilities to better use 3D models and other 3D data throughout the different stages of the planning and building process: idea, detailed planning, property formation, building permits, and management. The study focused on BIM for 3D property formation and pointed out three major fields in need of further investigation in the process of transferring from analogue 2D maps to a digital 3D cadastre and these are the legal matters, the financial aspects, and the technical matters in form of data conversion and visualization (Andreé et al. 2019, Larsson et al. 2020).

- *Testbädd för Smarta plan-, bygg-, förvaltnings- och nyttjandeprocesser över hela livscykeln*: several tools were developed for smart planning, construction, and management of BIM and city model data throughout the building life cycle. One work package was devoted to 3D cadastre, which mainly dealt with the issue of visualization of cadastre information. These results are interesting for the cadastral index maps part of this project.
- *3CIM*: A joint project between the three main cities in Sweden to create a Swedish profile of CityGML. In a later stage the 3CIM specifications could be the basis of a Swedish specifications of 3D cadastral index maps. More information is found in Uggla (2022) and at https://www.smartbuilt.se/projekt/informationsinfrastruktur/3cim/.

3 WP 1: Swedish lifecycle 3D property formation process

In this report we introduce a motivation and plan of how the case study was performed. The description starts by introducing the background in Section 3.1, and then providing the research question and purpose (Section 3.2). Section 3.3 is devoted to the methods and results of the BIM-based lifecycle 3D property formation process with a Swedish case study. The chapter ends with a discussion in Section 3.4.

3.1 Background and introduction

A cadastre contains property unit information (e.g. rights, restrictions and responsibilities) used in countries' legal system to define both the 2D and 3D property units. To form the property units, several actors are involved, foremost applicants, the cadastral authorities, land and environment court, local municipalities, and the national cadastral authorities. The cadastre process requires that the actors share and exchange cadastral information between each other. However, much of this information sharing is still using textual description and non-machine readable data formats. During recent years, there have been several studies of technical solutions for the cadastral process both from a technical perspective (Oldfield et al., 2017; Stoter et al., 2016; Sun et al., 2019) and a legal perspective (Swensson and Juulsager, 2014; Andrée et al., 2018).

Most documents used in the property formation process are recorded and registered in paper format or frozen digital images (Andrée et al., 2018). In Sweden, the cadastral authorities use 3D CAD drawings specifying the 3D real property boundaries in the cadastral formation process, but these drawings are not formally archived in the national real property register (Larsson et al., 2020). Moreover, the organizations and different stakeholders involved in the 3D property formation process reveals it as an unclear and ambiguous process. To overcome these problems, several authors have proposed a 3D cadastre process based on exchange of 3D digital models, especially BIM (see e.g. Olfat et al., 2019; Larsson et al., 2020). From a technical perspective, it seems that several of the standards are mature enough to support this exchange of data, e.g. the IFC format for BIM data.

In this work package, we have introduced a detailed process schema that describes the digital data delivery between the actors as well as actions from the actors to obtain an unbroken digital flow of data in the 3D cadastre process based on BIM. This process schema is evaluated from both a technical and a legal perspective in a Swedish case study. We use IDM, the process standard of BIM, to illustrate how data is exchanged and shared between different actors in the lifecycle phases when forming 3D property.

3.2 Research question and aim

One of the main rationalities behind the Smart Built Environment program is to extend the sharing of digital information in the built environment process. To illustrate the interactions and possible flow of information in the lifecycle 3D property formation process is very complex, and varies between different cases.

In order to investigate complex spatial structures and avoid ambiguous property boundaries, 3D property registration with technical support of integrated BIM/GIS can represent and form legal objects in a 3D reality world. Previous research by Sun et al. (2019) proposed a general framework to integrate 3D cadastre with BIM and 3D GIS among three organizations: cadastral unit, AEC Company and city surveying unit. However, there was no detailed description of the digital data delivery between the involved actors to obtain an unbroken flow of data in the 3D property formation process clearly. Within the 3D property formation process, main and practical difficulties are that when and what cadastral data should/will be exchanged and stored from/to who (organizations/ actors).

Therefore, the research question is:

- How to facilitate a lifecycle 3D property formation process that can clarify clearly how the involved actors exchange and share information with the integration of BIM and 3D GIS?

From a lifecycle perspective, this research question is aimed at facilitating a standardized and unambiguous digital process to illustrate how data is exchanged between different actors in the lifecycle phases when forming 3D property.

Therefore, the overall aim of this work package has been to facilitate a general, standardized and unambiguous digital 3D property formation procedure based on BIM in the lifecycle phases. The specific objectives were:

1) Which actors are normally involved in the process?
2) What kind of information is required and delivered in what order?
3) How do the actors share and exchange cadastral legal information and physical BIM/GIS models?
4) How to regulate information flow and improve information quality within processes?

3.3 Methods and case study

The proposed method aims to facilitate a general, standardized and unambiguous digital 3D property formation procedure on a national level in order to improve and enhance the digital Swedish Cadastral and Land Administration Systems. In the WP1, we propose a Swedish 3D real property formation process formalized in an IDM process map, which is based on the projects “*Data Quality and Data Responsibility within the Built Environment*” and “DigSam –digital community-building process”.

The IDM process is proposed to generally illustrate how the main actors cooperate, form and register 3D properties during the lifecycle phases. It is a developed 3D property formation process as a hybrid way of transition from 2D to full 3D that will improve the effect of registration process and optimize the registration compared with the current cadastral formation process. It embodies the digital cadastral management from legal, technical and organizational aspects.

Along with the description of the process below we also describe a case study performed on the property Organellen in Stockholm, Sweden. Organellen is located in Hagastaden, between Dalagatan and Norra Stationsgatan. The property Organellen includes two buildings in Stockholm with 195 apartments, both condominiums and owner-occupied apartments, as well as a parking lot. The project is under construction now, lead by Besqab Projekt & Fastigheter AB where the BIM model is created by Lindberg Stenberg Arkitekter AB. The cadastral dossier of Organellen is created and provided by the City of Stockholm who also provide the 3D city model used.

3.3.1 3D property formation phases

A lifecycle 3D real property formation process is proposed with four basic phases: initiation, preparation, decision and registration.

Figure 8. The four phases in the lifecycle 3D real property formation process.

Actors involved in the property formation vary in organizations, municipalities and countries. In this study, we identify five main actors according to the Swedish current cadastral procedure when forming a 3D property: applicants, the cadastral authorities, land and environment court, local municipalities, and the national cadastral authorities.

The role of main actors and their value are shown in Table 1. The cadastral authorities include cadastral surveyors that play an essential role during the 3D property formation process. The appointed cadastral surveyor by the cadastral authorities is in charge of the entire formation process that includes surveying cadastral boundaries (where applicable), making legal decisions for forming new property, changing a completed and registered property formation, rearranging related property rights and creating new rights (such as easement or right of way).

Table 1. The role and value of main actors.

Actors	Actors role and value
Applicants	Prepare a proposed 3D property model, submit an application and meet with the cadastral surveyors until sufficient documentation has been produced.
The cadastral authorities (including cadastral surveyors)	Responsible to check the application and assign cadastral surveyors that are in charge of the entire formation process including e.g. inspection and review of property units and property boundaries, making legal decisions, registration and update of 3D cadastral index map.
Land and environment court	If needed, both the applicant and local municipality can decide whether to appeal or not to the Land and Environment Court after receiving the decision information.
Local municipalities	Provide the access of relevant data, and coordinate ongoing parallel processes through consultation.
The national cadastral authorities	Responsible for registering and updating the 3D property into the national cadastral system.

3.3.2 BIM-based lifecycle 3D property formation process

Then IDM is utilized to design a developed process of Swedish 3D real property formation including five actors and detailed data exchange flow. Each of these actors and their activities are represented by a lane in the IDM process map. There is also one additional lane named "*Data exchange and store*" to illustrate the details of information flow that relative 3D cadastral data and models share, exchange and store through activities between actors. The input data is in grey colour and the output data highlights in orange and green colours. Parts of the IDM process map show in the Figure 9 and the whole IDM process map shows in Figure 10.

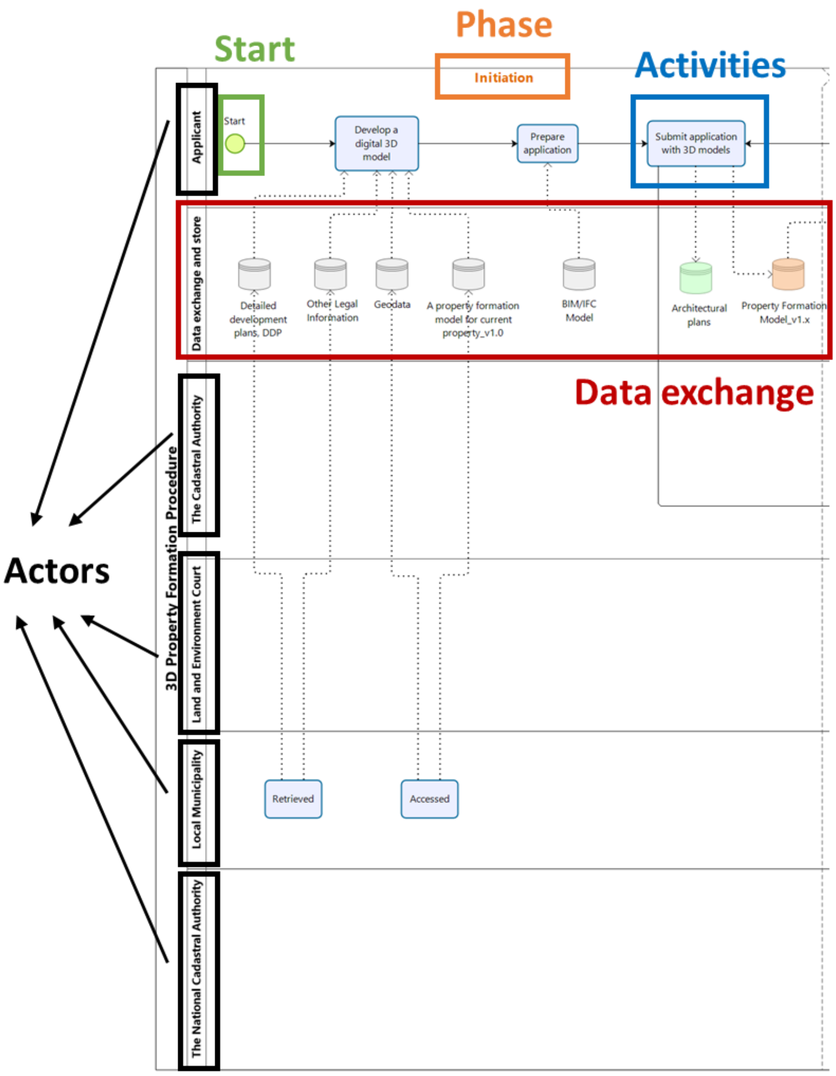


Figure 9. IDM process map.

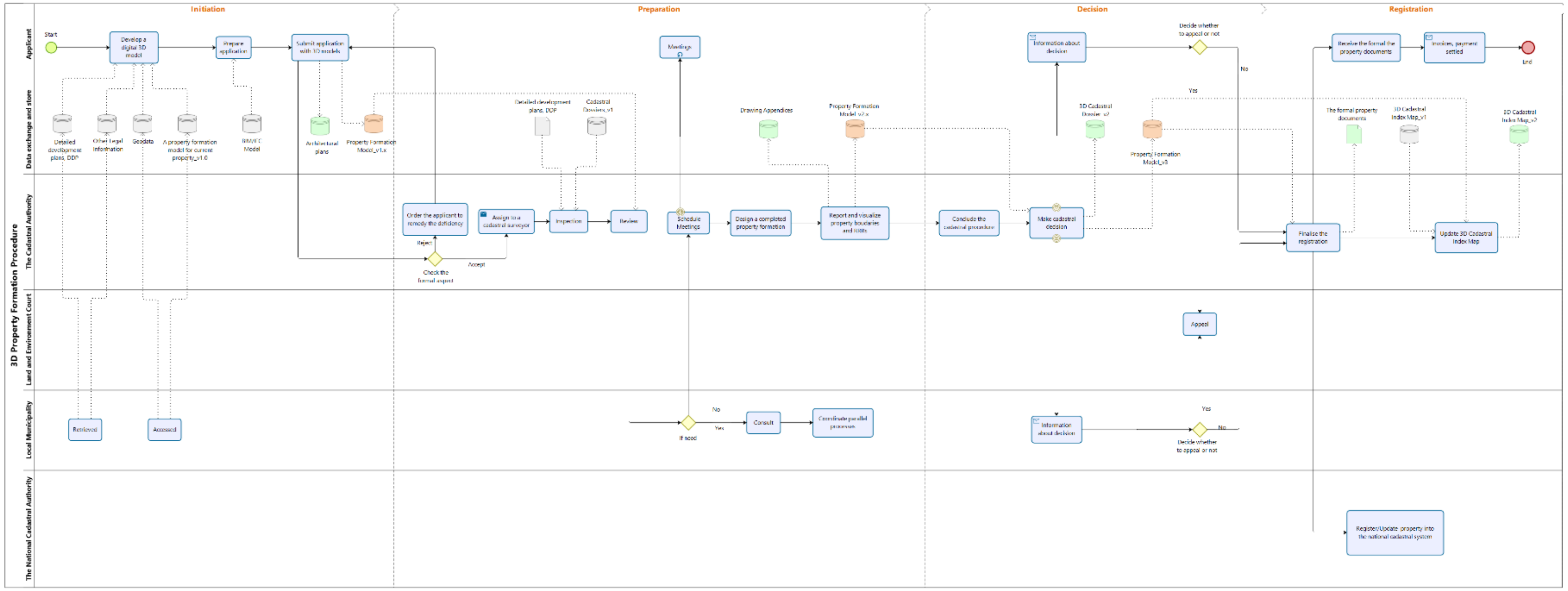


Figure 10. The IDM process map for lifecycle 3D property formation, see enlarged figures below (Figure 11, 15 and 18).

Each phase is explained in details following the IDM process from process and data (introducing the input and output data requirements and responsible actors/authorities in every phase) aspects, divided into three enlarged figures (Figure 11 for initiation phase, Figure 15 for preparation phase, and Figure 18 for decision phase and registration phase).

3.3.2.1 Initiation phase

The initiation phase of a 3D property formation process is where the applicant, typically a property developer, prepares and submits an application to the cadastral authority.

Process:

The initiation phase starts prior to the application for property development. The property developers or owners prepare and develop their digital 3D models by obtaining information via the local municipality which can be accessed online and from other sources for built environment data to build the 3D model, supplemented with the applicant's own building information for the new construction. This proposed process for 3D property formation presupposes that the current cadastral index map is updated to a 3D version. There is a more or less fully automated process for converting to the applicant's register model, which creates standard volumes for rights and 3D spaces. In order to get a more accurate account of each object, a review of decision documents etc. is required.

In connection with the application, the applicant produces supplementary documentation. The application is prepared by the applicant, sent to the cadastral authority and supplemented early in the process with a digital property formation model. This proposed property formation model is developed by the applicant from the 3D model according to guidelines / requirements by the cadastral authority for which objects are to be attached, some objects are always included, some never and others may depend on what the investigation of facilities etc. results in. The submitted model is a suggestion for property formation and has no legal force.

The applicant prepares the 3D property formation model including 3D property units and property boundaries following the detailed steps in Figure 11.

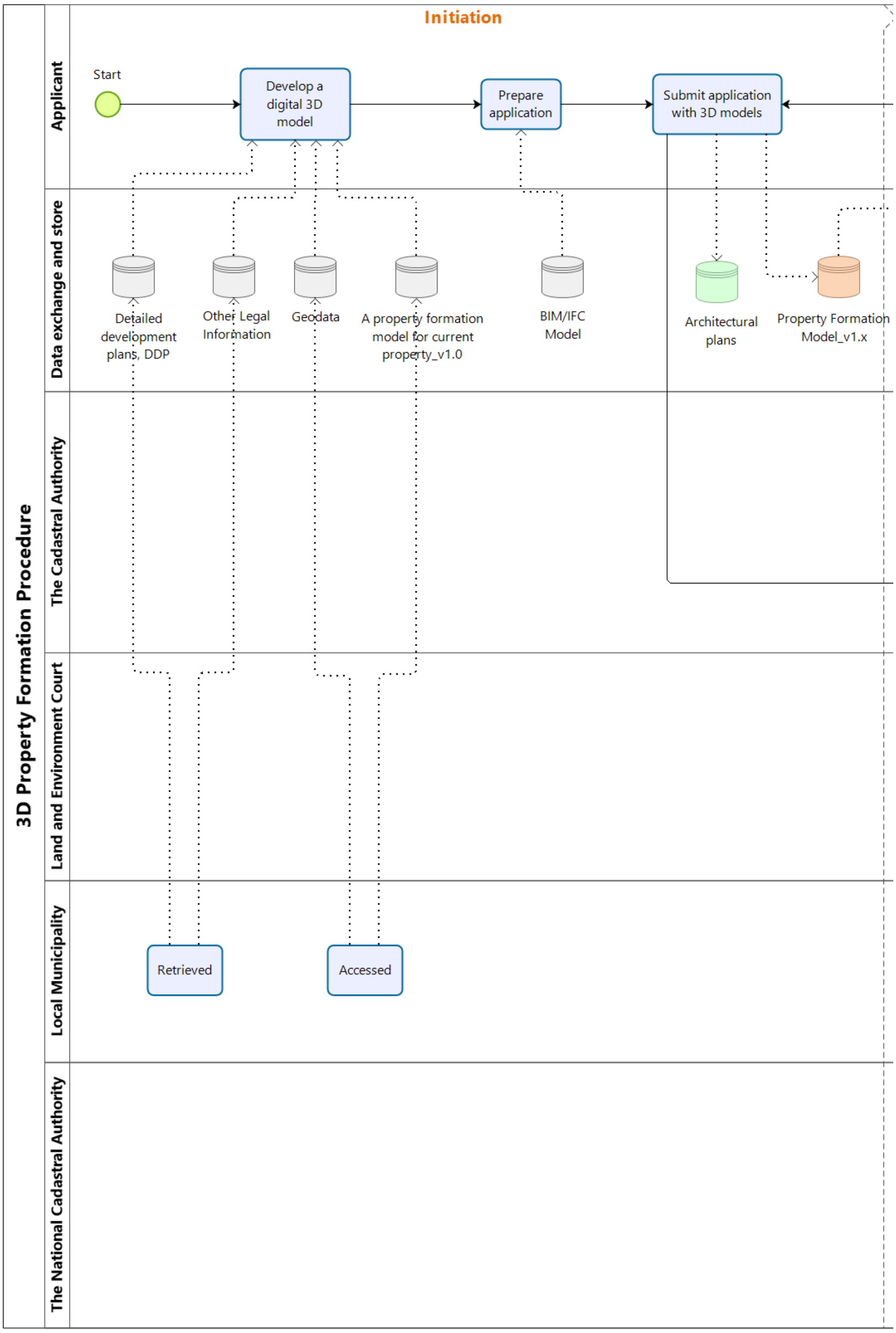


Figure 11. Initiation phase, enlarged from Figure 10.

Data:

The input cadastral documents, geodata and models for applicants to develop a digital 3D model can be accessed from the cadastral authorities and the municipalities. The input data may be various depending on different purposes and situation of projects. The detailed development plan (DDP, zoning plans) regulates the buildings in the area. Since 2022, all DDPs have to be in machine-readable form following the national specifications. The legal information of national and local regulations and geodata of relevant area are necessary to use to design and develop a BIM/IFC model of the 3D property units in order to meet all the cadastral legal requirements. An extract for the area can be submitted from the register model via the common platform if available. Copies of existing relevant property formation models and other decision documents can be obtained from the archive, which shows snapshots of constructions, property boundaries and rights, etc. from when the decision in each case was made. The extracts together with their own information and comparison with e.g. current planning regulations and building permits via the common platform can form the basis for a 3D model.

The BIM/IFC model could be an as-designed model (before construction begins) at LOD 300 level or an as-built (after construction has been completed) / as-is model (existing building) at LOD 500 level, depending on which stage the project is on. To create a 3D property formation model, the BIM/IFC model needs to be simplified and only keep necessary building elements to meet the cadastral legal requirements and to avoid redundant data storage. If there are existing CAD 2D plans or 3D geometry models, the CAD data could also be used to create a BIM/IFC model as the proposed 3D property formation model. Some input data (grey) and output data (colourful) are illustrated in the IDM process map that may be required, basic requirements of the data/model and responsible actors / authorities in the initiation phase.

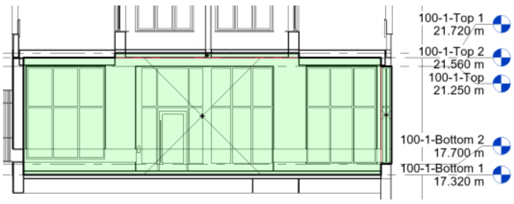
The output data is a proposed property formation model without legal force in BIM/IFC format generated by the applicant. The 3D property units are defined as closed 3D volumes and modelled as spaces and zones (or *IFCSpace*) in the BIM/IFC model. It is important that the proposed property formation model states both existing and proposed changed, revoked and new boundaries and rights, respectively. If there are general requirements formulated by the cadastral authorities, the applicant must be followed to generate 3D property units as well as property boundaries. Otherwise, the property boundaries need to be suggested and stated clearly and accurately by the applicant in the proposed property formation model. Combined with version management (Eriksson et al., 2021), the proposed 3D property formation model is exported with spaces and recorded as version 1.x in order to see in retrospect what changes took place with the cadastral procedure. Architectural plans created from the property formation model are necessary to illustrate the new property boundaries for each 3D property unit.

Case study:

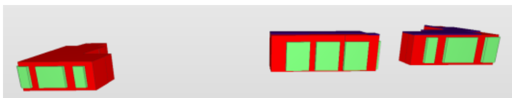
The new 3D property units are created in a simplified version of the BIM model (Figure 12a) that has only kept necessary building elements to meet the cadastral legal requirements and to avoid redundant data storage. The 3D property units are modelled as closed 3D volumes in the BIM model using Revit. In the case study, the property boundaries are generated following the suggested property boundaries. To create horizontal property boundaries, *space separator* is used to identify central, interior or exterior line of different building elements as boundaries, e.g. the central line of the inner walls, the interior line of external walls and the exterior line of windows. For different heights of vertical property boundaries, extra *sections* need to be manually added firstly. Then in each section view, *levels* corresponding to the suggested heights are created and if needed the heights of spaces can be adjusted (an example is shown in Figure 12b).

Spaces are created separately due to the spaces are bounded by different building elements in Revit. Figure 12c shows those spaces in the three property unit areas without building elements, visualized in Solibri. Red volumes represent main spaces, while green volumes for spaces of windows and blue for spaces of floors. Then separated spaces are grouped into *zones* (named Organellen \100\1, \100\2 and \100\3 respectively) to represent the legal property unit areas.

a. The original BIM model of Organellen, Stockholm, Sweden.



b. Example of creating different heights of vertical property boundaries, view of Section A.



c. Three property units of Organellen 100, visualized in Solibri without building elements (Red volumes represent main spaces, green volumes for spaces of windows and blue for spaces of floors).

Figure 12. Case study of Organellen, BIM / IFC models and the 3D property units.

The proposed property formation model is thus generated with spaces as 3D property units and spaces boundaries as property boundaries, recorded as the property formation model_v1. Figure 13 shows the property formation model_v1 with created spaces and spaces boundaries for the three property unit areas of Organellen 100, of which the left is with all building elements and the right is without external walls.

Figure 13. Left: the property formation model_v1, with created spaces and spaces boundaries for the three property unit areas of Organellen 100. To the right, the model is shown without external walls.

The application should also include the architectural plans that illustrate the new 3D properties. These floor plans are generated from the 3D property formation model, which are shown in Figure 14.

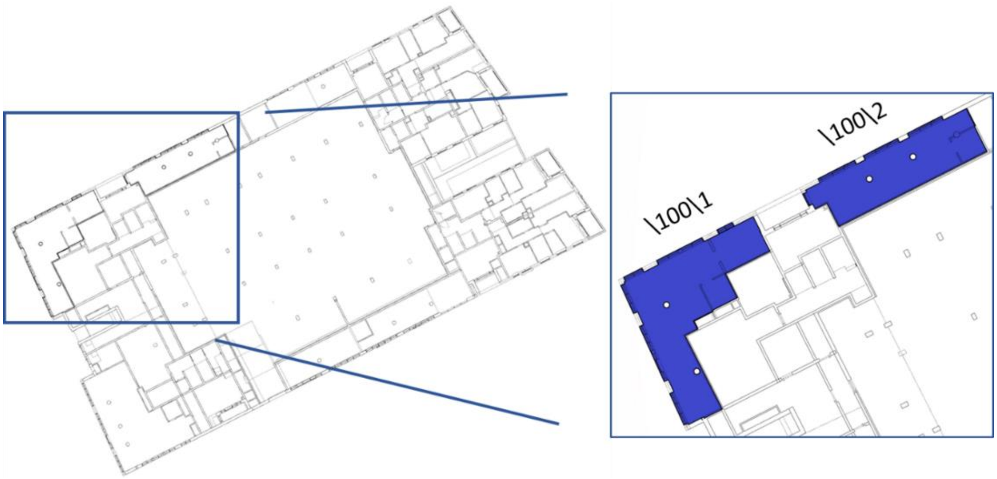


Figure 14. Architectural plan that illustrates Organellen \100\1 and \100\2, at Plan 10. The floor plan is generated from the property formation model in Figure 13.

Finally, the applicant submits a 3D property formation application of Organellen including the proposed property formation model (version 1) (in IFC format) and the architectural plan illustrations to the Stockholm municipality (in PDF format).

3.3.2.2 Preparation phase

In the preparation phase, the main activities are done by the cadastral authority.

Process:

The preparation phase starts with the cadastral agency checking the application, which is returned to the applicant if incomplete or containing errors. After checking and further preparing the application, a cadastral surveyor is assigned to the case. The cadastral surveyor examines the suggested property formation against current legislation (mainly the Property Formation Act, FBL) as well as other applicable planning regulations and given building permits for the area concerned. When testing suitability, etc., the need for changed and / or additional rights and demarcations may arise.

The cadastral surveyor inspects the proposed property formation model, architectural plans and the necessary cadastral map on footprint level, for example property boundaries and easements, against current regulations in 3D. The DDP is used to regulate the buildings in the area. The cadastral surveyor reviews the suggested property boundaries of the 3D property units and the need for RRRs. It is important to check that the 3D property formation models_v1.x does not violate any rules in the detailed development plan, e.g. that a 3D property is proposed for a purpose that is not allowed in the area.

Complete documentation needed for the property formation is generally not ready in connection with the application and one or more meetings are held with the applicant(s) until sufficient documentation has been produced. If needed, the cadastral surveyor will consult with the local municipality (typically regarding water supply, sewerage, and/or development plan issues) and/or regional or governmental agencies, such as the national Road Authority (typically regarding road access). The property formation version model_v1.x may be changed and updated to new versions – property formation model_v2.x – in cooperation with the applicant by the cadastral surveyor during the preparation phase. Ongoing parallel processes for building permits and detailed plans are coordinated through consultation and/or other contact with the relevant stakeholders. During this process, the cadastral surveyor prepares drawing appendices of a draft decision based on the documentation received from the applicant. These documents consist typically of an administrative (cadastral) map, description and minutes.

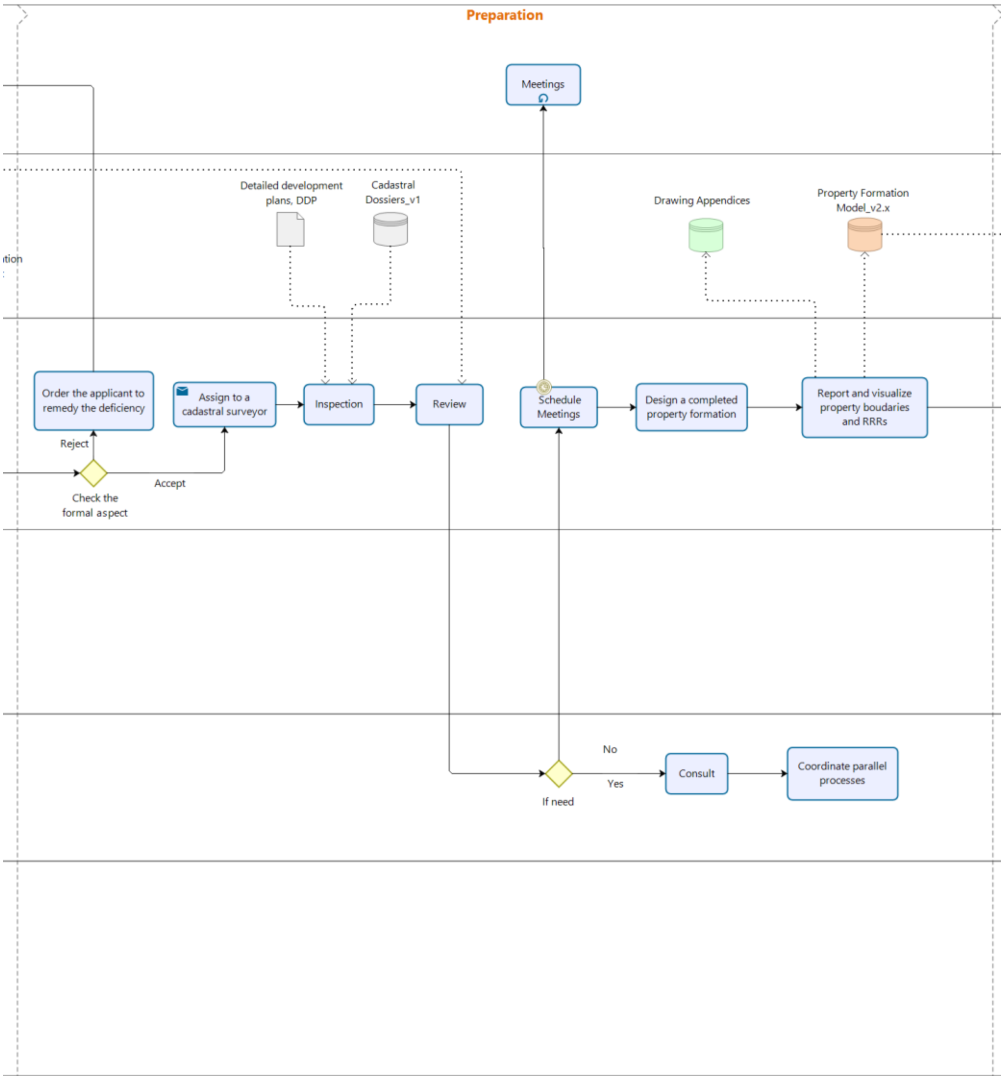


Figure 15. Preparation phase, enlarged from Figure 10.

Data:

The input and output data are managed in version, shown in Figure 15. The input data is application documents, including 2D/3D cadastral dossiers (if there are existing cadastral dossiers) and other information such as e.g. DDP and the proposed property formation model (version 1.x, generated by applicant in the initiation phase).

The output data is a 3D property formation model (updated version 2.x) and the drawing appendices. The description of a draft decision normally refers to drawing appendices that report details about 3D spaces and relevant rights. Analogue or digital construction drawings showing the maximum extent of the

3D space in horizontal and/or vertical planes are usually produced by the applicant, in consultation with the cadastral authority. The 3D property formation models_v2.x is necessary for keeping the model up to date and resolving potential conflicts as preparation progresses.

Case study:

Figure 16 shows an example of how the 3D property unit and property boundaries of Organellen \100\1 are inspected and reviewed in Solibri, as well as checked the relationships of IFC spaces and building elements in Figure 17. A relation between the outer wall and the main space volume 3 is indicated with an arrow, which can have information about the kind of ownership that is defined for example surface to surface, 50% of the thickness of the wall etc.

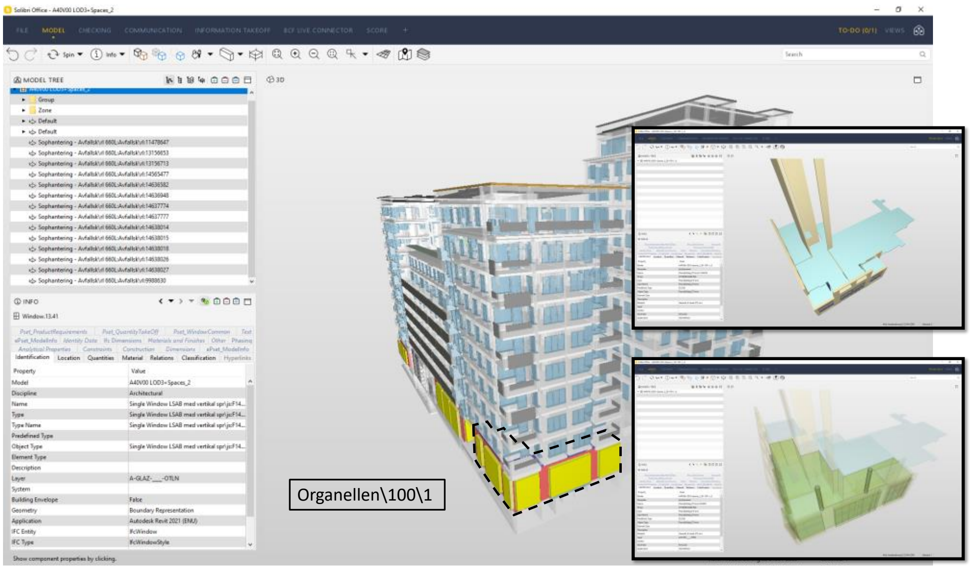


Figure 16. 3D property unit and property boundaries of Organellen \100\1 are inspected and reviewed in Solibri.

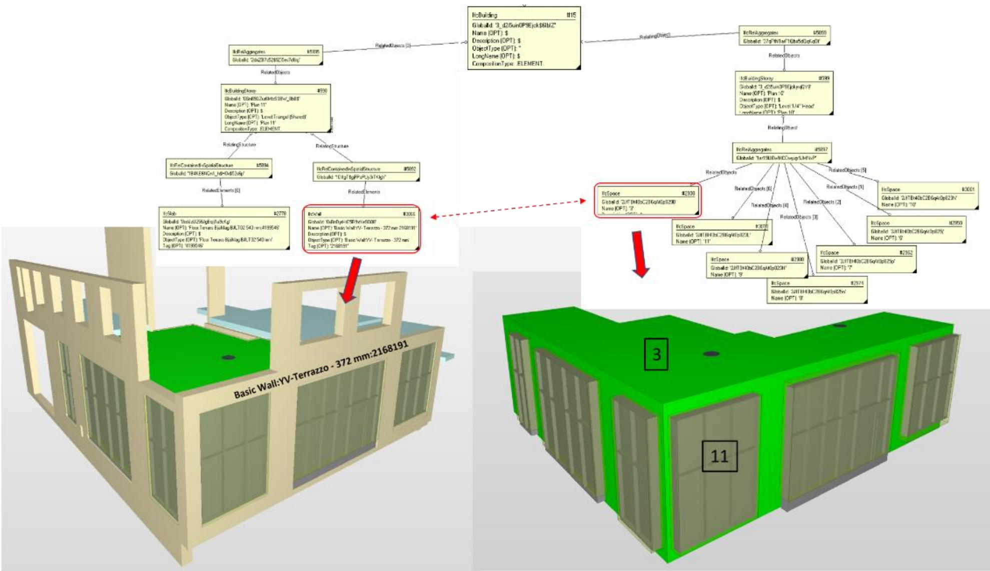


Figure 17. The relationships of IFC spaces and building elements of Organellen \100\1. An example of the relation between the outer wall and the main space volume 3.

3.3.2.3 Decision phase

Process:

The cadastral surveyor will conclude the cadastral procedure and make a final decision. The actual cadastral decision is central for forming a new property unit for e.g. housing purposes, legalizing the existence of the newly formed property (FBL, 1970, 4 chap. 25 a §). A final version of 3D property formation models_v3 is exported based on the previous version and stored after the final decision has been made, which can be used to update the 3D cadastral index map in the registration phase. Both the applicant and municipality will receive the decision information and decide whether to appeal or not to the Land and Environment Court. The cadastral decision is confirmed by the cadastral surveyor. The decisions include, most importantly, the assessment of whether the intended real property unit is enduringly suited to its purpose, which is a legal requirement for its creation (FBL, 1970, 3 chap. 1 §). In addition to this, information from the property register and the digital index map (which serves as an overview basis) is used.

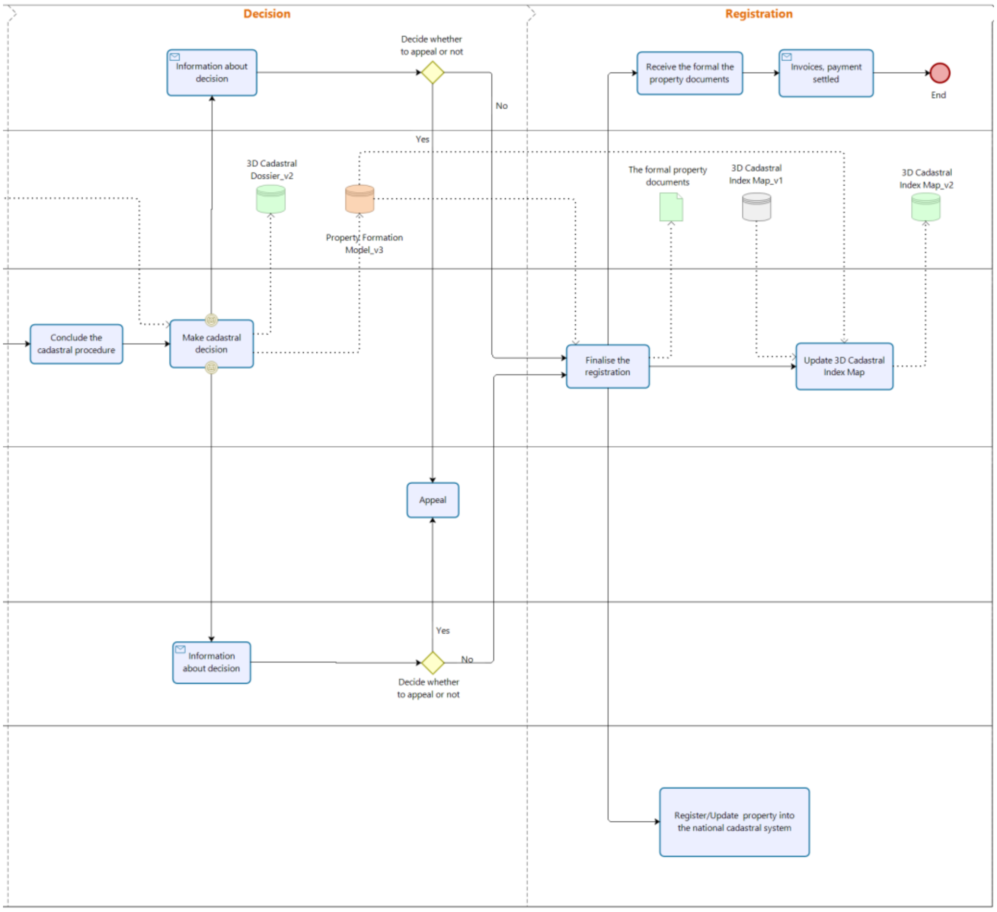


Figure 18. Decision phase and registration phase, enlarged from Figure 10.

Data:

The 3D property formation models_v2.x is used as input data. The output data is the 3D cadastral dossier, including map, description, minutes, 3D property formation model (updated version 3), and appendices. The 3D cadastral dossier is created / updated (if there are existing cadastral dossiers) and includes the property formation model_v3. Currently, the decision documents are in paper format, and this also applies to previous cadastral decisions as well as current planning regulations and decided building permits that are used as a basis. A legal change is required to make the decision documents archived in digital format (e.g. 3D PDF) to have a legal status.

***Case study*:**

The final decision includes a property formation model in IFC format (3D property formation model) as well as description, 3D visualization of the property formation model in 3D PDF (shown in Figure 19), architectural plans, minutes, and appendices which are stored in the 3D cadastral dossier.

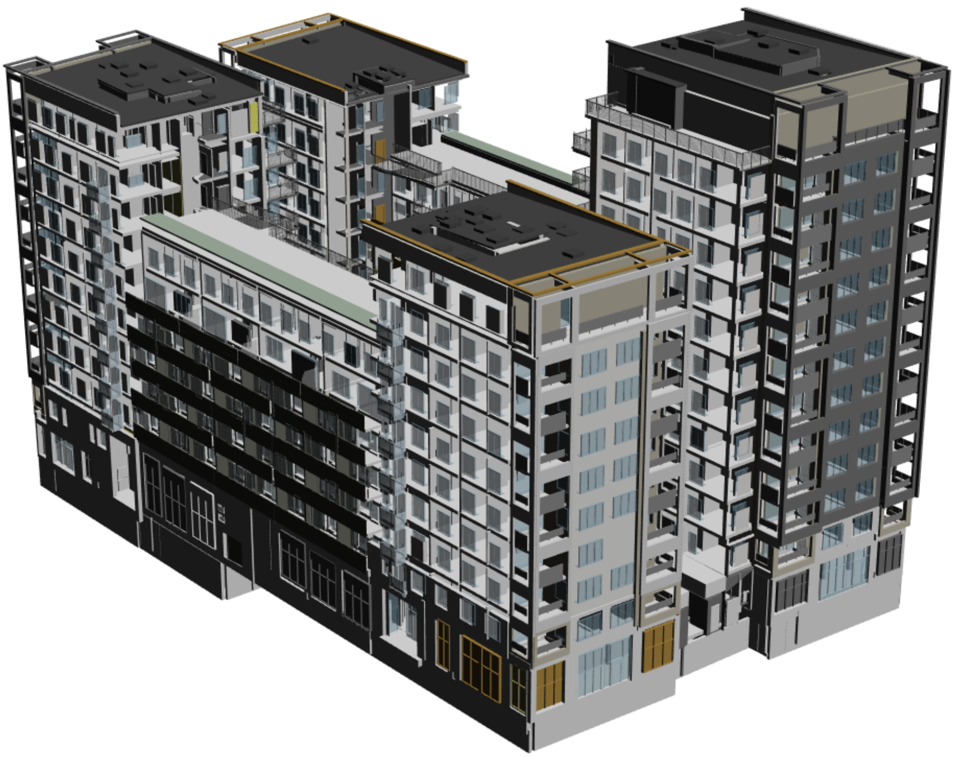


Figure 19. Visualization of the property formation model in 3D PDF.

3.3.2.4 Registration phase

Process:

The cadastral surveyor finalizes the registration of the new real property in the Real Property Register national cadastre after the mandatory appeal period has ended and no appeals have been made. Finally, the applicant receives the formal property documents and the property formation process ends after the payment is settled. Meanwhile, the cadastral dossier is stored in the agency's digital archive. The new or altered 2D and 3D real properties are registered in the agency's archive and shown in the 3D cadastral index map. The cadastral surveyor updates the property register and the 3D cadastral index map when a cadastral decision has gained legal force. Archive files are archived separately, and can be accessed via a link in the property register. The cadastral surveyor will update new 3D property units in 3D city models after registration. See Figure 18.

Data:

The input data is the 3D property formation models_v3 that is utilized to finalize the registration, as well as to create a 3D cadastral index map or to update the 3D cadastral index map (if there is an existing 3D cadastral index map). After finalizing the registration, all the cadastral information should be stored in the formal property documents.

Case study:

The cadastral surveyor finalizes the registration of Organellen as a new real property and registers to update the 3D cadastral index map (see Figure 18). The buildings in the cadastral index maps consist of the Organellen building generated from the BIM model and surrounding buildings from the City of Stockholm 3D building model. All the data is transformed (to a common geodetic reference system), converted and integrated by using FME, and then Google Earth is used for visualizing the 3D cadastral index map (Figure 20).

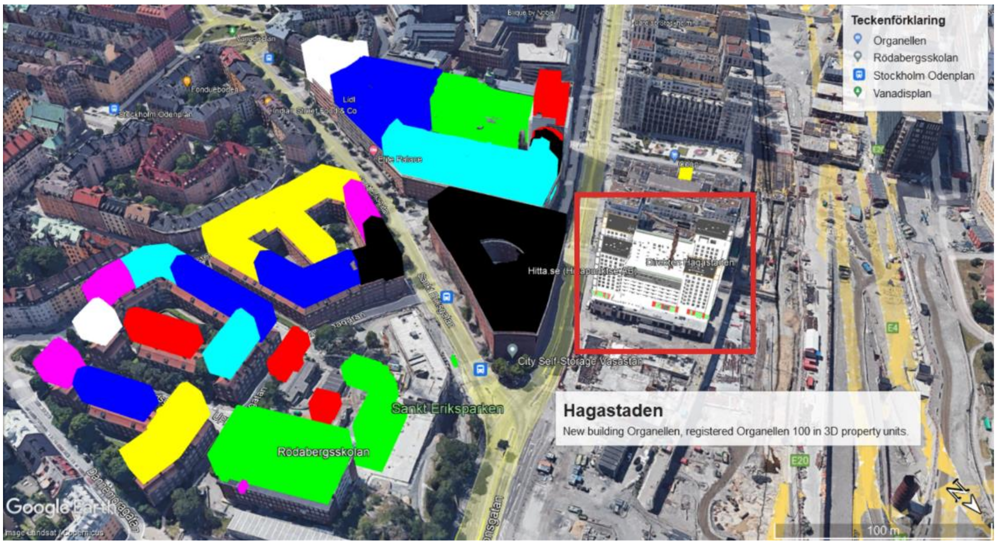


Figure 20. Visualization of the updated 3D cadastral index map in Google Earth (new 3D properties shown in red rectangular).

3.4 Findings and limitations in the work

In this case study we have focused on developing a BIM-based Swedish 3D real property formation process in lifecycle consisting with four phases: registration, initiation, decision and preparation. The IDM process has illustrated the details of information flow that relative 3D cadastral data, 2D/3D GIS data and BIM/IFC models share, exchange and store through activities between actors. However, the detailed 3D property formation process for individual 3D properties may vary in complexity from different requirements of legal regulations in different municipalities, to practical situation of different projects, to different actors involved in the property formation process.

The research question given in Section 3.2 emphasizes three points: a lifecycle 3D property formation process, actors' responsibilities and activities, and information exchange and share. IDM was used to design a developed process for the Swedish case study in order to facilitate a lifecycle 3D property formation process with clear data exchange flow. During the process, the BIM/IFC models were used to generate 3D property formation models that would be managed in version for sustainable cadastral management. Nonetheless, individual 3D properties formed may vary in the process due to different practical situation, requirements of legal regulations, and actors involved. Thus, general guidelines/requirements are suggested to be formulated by the cadastral authority for clarifying actors' responsibilities and guiding actors' activities. Moreover, it should be aware of the challenges to put the proposed process into practice and legal changes in national standards are required to realize 3D property formation legal force.

A practical and essential problem is how to make 3D models with legal force to register and store the legal information. 3D PDF may be a transitional way (BIM/IFC models can be exported or converted to 3D PDF) as 3D property formation documents with legal force and easier to be accepted by the Swedish cadastral authorities. The problems of legality, validity and storage of the process and 3D models in practice should also be noticed.

The case study has revealed several technical challenges:

1) Defining the 3D property in the BIM model. There need to be guidelines of how this should be performed by e.g. linking the property borders to physical object (walls, etc.) in the BIM model.
2) The process of georeferencing of the BIM models needs to be improved. There are several problems here such as lack of georeferencing parameters in the BIM files, interoperability problems of tools to export these parameters to IFC (see e.g. Noardo et al. 2020) and limitations of 3D GIS tools to read georeferenced BIM models.
3) Presentation of 3D cadaster index maps in Google Earth is not an ideal solution. What is missing at current at this stage is a national profile for city models (based on the international standard CityGML) with added specifications of how to represent 2D / 3D property units. An embryo of that has been created in the 3CIM projects, but more works need to be specified of how to handle logical spaces. This is part of the new CityGML 3.0 standard, which is still in an early phase that lacks good implementations.

There are also other challenges, not studied in the case study. One such challenge is the life cycle perspective of the BIM model in conjunction with the definition of the 3D Cadaster (based on the BIM model) at a single time.

4 WP 2: Cadastre Ecosystem

In this report we present a conceptual definition and framework of how the work package was performed. The description starts by providing the research questions and aims (Section 4.2). Section 4.3 is devoted to the methods and results of the proposed organizational cadastral management based on business ecosystem and cadastre ecosystem. The chapter ends with Section 4.4 that discusses the results of the case study.

4.1 Background and introduction

Within the rapid, and increasingly sustainability focused urban development, 3D cadastre is increasingly being integrated with 3D physical models to represent and visualize 3D real property with RRRs (van Oosterom, 2013). Paulsson and Paasch (2013) divided 3D cadastral research on 3D cadastre into four main categories: legal, technical, registration and organizational. Large parts of 3D cadastral research focus mainly on the technical aspects, but also on legal aspects such as legal framework, 3D property rights, and 3D cadastre visualization (Shojaei et al., 2013; Paasch and Paulsson, 2014; El–Mekawy et al., 2014; Li et al., 2016; Atazadeh et al., 2017; van Oosterom et al., 2019; Sun et al., 2019; Çağdaş et al., 2020). Some research concerns the registration of 3D property (Stoter et al., 2017; Oldfield et al., 2017; Hjelmblom et al., 2019; Sladić et al., 2020; Sun et al., 2021), while there are few research studies on the organizational issues (Zysk et al., 2020; Saeidian et al., 2021). However, from the organizational and business perspectives, there is a need to explain how actors can be managed in the context of 3D cadastre. The development of organizational and business perspectives of 3D cadastre requires the clarification of how various involved stakeholders and other actors are interconnected to achieve business goals, such as value creation, and to minimize time and cost consumption.

In the case of 3D cadastral management, actors who contribute to, and benefit from cadastre systems include governmental agencies (e.g. cadastre authorities, courts and local municipalities), applicants (e.g. owners), industry firms (architecture, engineering, construction and operation (AECO) companies), and the public. The relationships and network of these actors are complex, especially when integrating with BIM and 3D GIS. Saeidian et al. (2021) listed private and public stakeholders involved in underground land administration and suggested to establish the relationship between involved parties and to define an administrative framework. Therefore, how to coordinate the complex network of actors and collaborate effectively are situations and challenges that 3D cadastral management is facing presently.

4.2 Research question and aim

In the case of 3D cadastral management, actors who contribute to, and benefit from cadastre systems include governmental agencies (e.g. cadastre authorities, courts and local municipalities), applicants (e.g. owners), industry firms (architecture, engineering, construction and operation (AECO) companies), and the public. Besides issues of integrated technology and processes, current 3D cadastre lacks clarification of the complex network of various involved actors and poses challenges to coordinate the actors. From the organizational and business perspectives, there is a need to explain how actors are interconnected and how to achieve business goals, such as value creation, and to minimize time and cost consumption. Therefore, the research question of this work package is:

- How to manage 3D cadastre sustainably and holistically from organizational and social perspectives?

This work package aimed to better understand and address the actors' coordination and collaboration issues from organizational perspective of 3D cadastre, as well as further manage 3D cadastre from a strategic point to achieve sustainable cadastre. Therefore, the specific objectives were:

1) What are the motivations and practical problems for different stakeholders involved in 3D cadastre?
2) Besides integrated technology, how to manage 3D cadastre from social and organizational perspectives?
3) How to identify the complex actors' positions and relationships?
4) How to clarify the involved actors' role, value and propositions?
5) How to encourage different actors sharing and exchanging data and information for 3D cadastre?

4.3 Methods and results

4.3.1 Organizational 3D cadastral management

4.3.1.1 Motivations

To address the problems, we considered the following key motivations of introducing business ecosystem for 3D cadastral management:

1) Identify actors' positions and relationships: During different processes of 3D cadastre, involved stakeholders depend on the purposes of 3D cadastre, such as 3D cadastral registration, commercial transactions, land valuation and digital twin. Related stakeholders include governmental and private organizations, as well as individual actors. Different countries have their own management agencies, but similar stakeholder engagement. Governmental organizations are mainly cadastral authorities, local municipalities, as well as related national or local courts. Private organizations could be architect companies, construction companies, banks, survey companies and even consultant

companies. Individual actors include actors like owners, cadastral surveyors and technicians (could be employed and appointed by governmental organizations), the public, and notary. The network of actors is complex and thus, it is important to identify the positions of internal and external actors and connected relationships, which is helpful to clarify that what are the involved actors' responsibilities.

2) Clear actors' roles and values: Considering 3D cadastre as an integrated application, however, it has to face possibilities of unclear management between stakeholders due to unsolved legal and technological problems (for example no unified international standards of cadastral data, no comprehensive guidelines for 3D property registration, and no detailed requirements for cadastral stakeholders during property management). For a common example, ambiguous management of the 3D property formation process may lead to indefinite responsibilities between different stakeholders, even giving rise to prevarication responsibility. To address these concerns, it needs to clear involved actors' roles and values in order to elaborate how to divide actors' responsibilities. In the business ecosystem-based 3D cadastral management, each stakeholder would affect and be affected by the others to align their core purpose and create a sustainable value collaboratively.

3) Encourage internal and external actors: the motivation for different stakeholders to share information depends on their roles and values. Traditionally, there are conflicting goals for information use between private and public actors. Private actors want to own information and use it for the development of their own commercial services, and public sector actors want to make information publicly available so that many private actors can use the information. However, there is a growing insight among private actors that information sharing also results in growing markets, and so sharing of information in-between private actors can increase the market for several commercial actors. Sharing of information between public actors and private actors, e.g. BIM companies, will improve the overall application and increase value for each other. Therefore, it is beneficial to encourage both internal and external actors in order to motivate dynamic interactions. The effect of those dynamic interactions in the business ecosystem-based cadastral management will be profound implications from an organizational perspective.

4.3.1.2 Business ecosystem-based 3D cadastral management

As introduced in the Section 2.3, the business ecosystem enables to provide opportunities to understand the interconnections between different actors through lifecycle phases. To clarify the complex relationships and solve ambiguous responsibility between different stakeholders, a conceptual definition of business ecosystem-based 3D cadastral management has been proposed and designed in this study.

Through adopting Moore's framework (core business, extended network, and business ecosystem), the business ecosystem-based 3D cadastral management consists of a network of interlinked stakeholders as a corresponding combination of stakeholders' positioning. Each stakeholder would affect and be affected by the others to align their core purpose and create a sustainable value collaboratively. The Swedish 3D property formation process is taken as an example to explain generally how to build a business ecosystem-based 3D cadastral management for the registration perspective. (Figure 21).

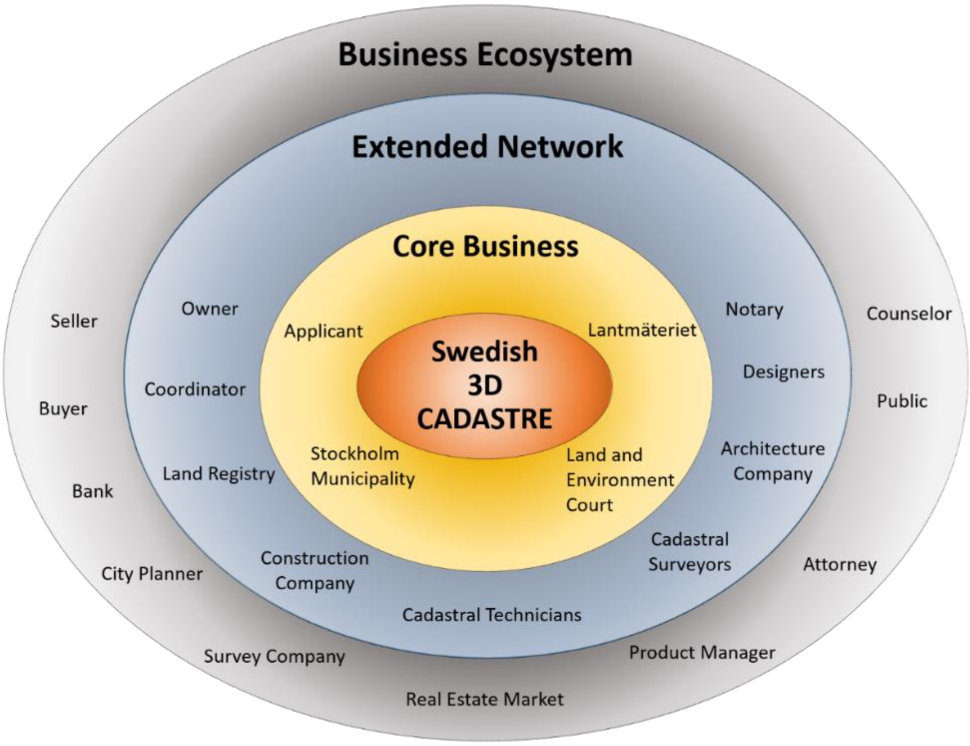


Figure 21. A Moore's network for Swedish 3D property formation on three levels (core business, extended network, and business ecosystem).

Furthermore, from views of value creation, to some extent of 3D cadastral management, it is both collective and individual, independent and interdependent, standard and specific, controlled but non-hierarchically governed. In other words, no single actor alone can coordinate the entire ecosystem alone and thus the responsibility for cadastre management is divided among several organizations. It aims to clarify the complex network of various involved stakeholders and streamline the 3D cadastral management to minimize time and cost consumption.

The business ecosystem-based 3D cadastral management enables to decrease communications barriers, engage various stakeholders, facilitate actors' network visible, clarify actors' roles and values, and accelerate digital organizational management.

In addition to theoretical understanding of the business ecosystem-based 3D cadastre management, we believe that the definition may also improve strategic analysis about 3D cadastre management, as the concept can be expanded into a holistic framework for cadastre ecosystem (for more details see Section 4.3.2).

4.3.2 Cadastre ecosystem

The foundation of traditional cadastre consists of land, people and RRRs (FIG, 1995). However, we believe that the most important effects of 3D cadastral management is the ability of developing and managing 3D cadastre digitally, holistically and sustainably.

Recently, Habib (2020) designed a strategic framework for building a potential cadastral system in post-conflict Syria by using a logical framework approach. Hämäläinen and Krigsholm (2022) found that the strategy goals and strategy drivers of national mapping, cadastral, and land registry authorities converged largely and related particularly to digitalization, data properties, customers and needs of society, as well as organizational development.

Different actors are involved in various cadastral processes, and these actors and processes are affected by various policies, technologies, and business needs. Therefore, the 3D cadastral management increasingly needs to consider strategically from the wider ecosystem – Cadastre Ecosystem.

By expanding business ecosystem-based 3D cadastral management to cadastre ecosystem, we propose a conceptual framework of cadastre ecosystem with five general components: policy, people, process, technology and business in Section 4.3.2.1. Moreover, a conceptual analysis is presented to illustrate the relationships of the components in the cadastre ecosystem framework in Section 4.3.2.2.

4.3.2.1 A conceptual framework of cadastre ecosystem

To achieve the purpose of sustainable 3D cadastral management, from a strategic point of view in the study, we further propose a concept framework of cadastre ecosystem with five main components: policy, people, process, technology, and business (Figure 22). The framework operates at a generalized level. The application of the framework, for example, in different countries could thus deepen the conceptual analysis presented here. Hämäläinen and Krigsholm (2022) pointed out that the strongest drivers of strategy work are changing customer needs and policy changes by the government. The proposed framework identifies 3D cadastral management by components that dynamically link to each other, thereby giving rise to the cadastre strategic initiatives. These five components could cover legal, social, organizational, technical and economic perspectives.

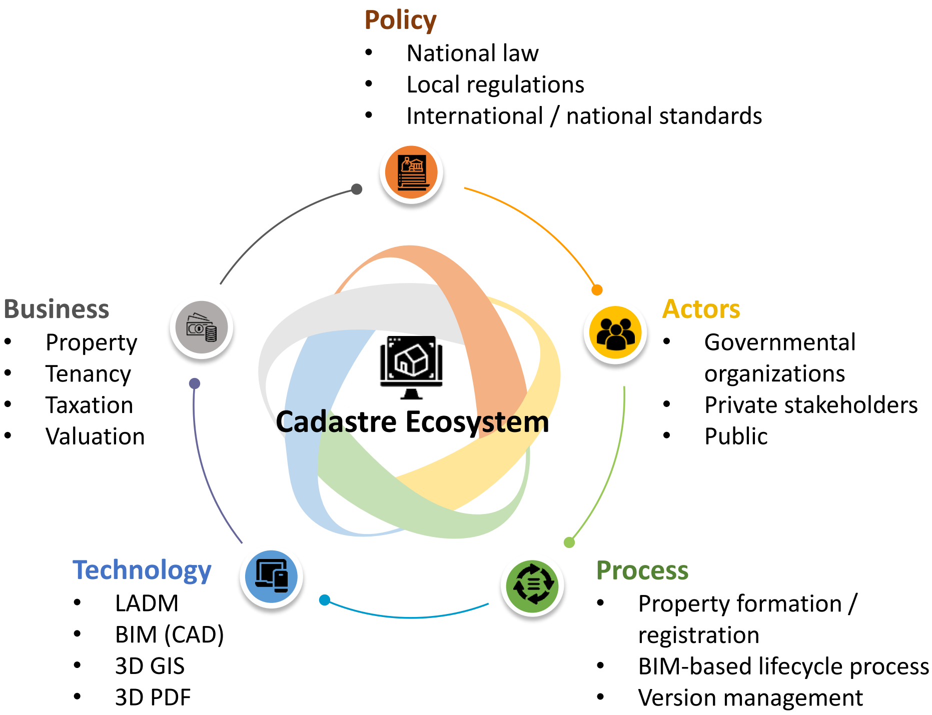


Figure 22. Conceptual framework for cadastre ecosystem with five main components: policy, people, process, technology and business.

4.3.2.2 Relationships between components of cadastral strategy

For the conceptual framework, we have designed a network model of components that requires attention to, and consideration of, the linkages among five components (Figure 23). Identification of mechanisms that govern the functioning of cadastre ecosystems is important for removing bottlenecks in the 3D cadastre development (Çağdaş et al., 2020; Jacobides et al., 2018; Eriksson et al., 2019; Zahra and Nambisan, 2012). Figure 23 and the following analysis explicate these mechanisms. Each ecosystem component is interrelated and interdependent of other components. The network model identifies 20 mechanisms (unidirectional arrows) between the cadastre ecosystem components.

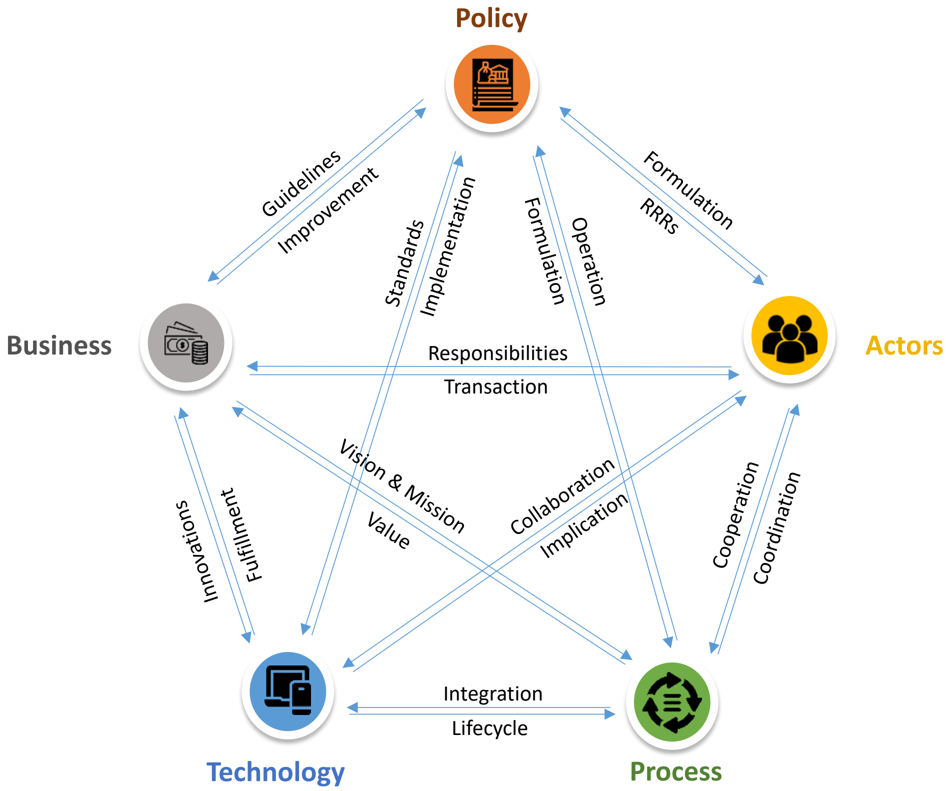


Figure 23. The network of relationships between components of cadastral ecosystem.

4.4 Findings and limitations in the work

As introduced, 3D cadastre has attracted increasing interests but is mostly utilized in large cities. BIM is proven as a sustainable method in the lifecycle process in the WP 1, but mainly focuses on a technical management perspective. Practical application of 3D cadastre relates to various stakeholders. To motivate those involved stakeholders, in the WP 2 we proposed to utilize a business ecosystem approach for organizational and social management of 3D cadastre.

The business ecosystem-based 3D cadastral management is inter-organizational and collective due to mutual dependencies that enable the ecosystem-level value creation. It will be reinforced by a collaborative network of cadastral organizations and reduce the risks of errors and overall costs in the 3D cadastral processes.

Cadastre ecosystem has abilities to facility policy implementation, coordinate actors' collaboration, improve processes efficiency, achieve technology integration and innovation and create value across multidisciplinary complementary contributions. The framework of cadastre ecosystem demonstrated that cadastre is developing gradually from 2D cadastre with legal information, then 3D cadastre registered and managed with 3D physical models, later 4D cadastre with continuous phases in lifecycle process, further 5D cadastre considering economic aspects, and lastly to sustainable cadastre.

However, the method was conceptual and strategic rather than producing tangible results. For practice situation, no business model has been made for the business ecosystem-based 3D cadastral management, which aligns profit and purpose as well as supports the sustainable cadastre. The reason is that it is difficult to design an accurate business model to manage 3D cadastre without practical projects. Interviews of different stakeholders would be favorable to be carried out. Nevertheless, with a holistic view of digitalized cadastral management, it is possible and beneficial to use a business ecosystem approach to manage 3D cadastre from organizational and social perspectives sustainably.

5 Concluding remarks

This report is a summary of the results from the project "BIM-based 3D cadastral management", as a continuous research of the project "Data quality and data responsibility in the built environment" which are both parts of the research platform of the programme Smart Built Environment.

The report is resulting from the two work packages of the project including the project initiating and selection of scenarios, case studies, on which the work was focused, as well as the output of these two work packages.

The report includes a description of 2D and 3D cadastre and cadastral management, BIM including IFC, IDM and LOIN, as well as business ecosystem. Within the text, the two work packages were motivated and presented by the use of Swedish cases studies.

5.1 Conclusions and contributions

The WP1 proposes a BIM-based method to form 3D property for a sustainable 3D cadastral management. From organizational and legal perspectives, the IDM process illustrates the detailed procedure of 3D property formation and the data exchange between different actors in the lifecycle phases. From a technical perspective, a property formation model is proposed to use as main register model to represent and visualize the 3D property units and property boundaries.

With a holistic view of digitalized cadastral management, the proposed 3D formation property process has the possibility to increase efficiency and improve cadastral information exchange. The proposed methods optimize the current registration from the legal aspect, improve the efficiency of registration process from the technical aspect, and embody the digital cadastral management from the organizational aspect.

The business ecosystem-based 3D cadastral management enables to decrease communications barriers, engage various stakeholders, facilitate actors' network visible, clarify actors' roles and values, and accelerate digital organizational management. It is conductive to the promotion of organizational and social perspectives of 3D cadastral management. The effect of those dynamic interactions in the business ecosystem-based 3D cadastral management will be profound implications from an organizational perspective to accomplish ecosystem-level business value creation.

The cadastre ecosystem provides possibilities to develop and manage 3D cadastre digitally, holistically, strategically, and sustainably. The implication of the cadastre ecosystem is of strategical importance to the 3D cadastral management, that international cadastral standards are central for 3D cadastral management, that the cadastre ecosystem influences how to collaborate and manage the 3D cadastre, as well as how to develop the 3D cadastral business sustainably.

5.2 Discussion and recommendations

Based on the findings discussed in the previous sections, the authors provide five recommendations that would holistically facilitate the digitalization of the lifecycle 3D cadastral management and accelerate the development of the cadastral ecosystem sustainably.

The recommendations are from five aspects:

1) Policy: For a strategic and sustainable view, policy development of 3D cadastral management should include the advancement, modification and implementation of laws, regulations and standards that influence organizational change, improve the cadastral process, promote technology integration, and encourage actors' behaviour. Current cadastral policies need to be renewed in many municipalities and at national level in order to institutionalize and digitalize fully 3D cadastral management. Furthermore, policy may also act as an instrument for international collaboration in cadastre management, where increased international policy making, technologies integration and standardization, as well as business that cross international borders, may, if successful, lead to policy convergence in the future.

2) Actors: Cadastral authority, local municipality and cadastral surveyors, as official representatives and core members, should consider the role of other stakeholders and decide the basic process for 3D property formation in order to encourage and motivate private actors actively. On the other hand, to be adopted in practice, an ecosystem business model needs to be developed that generally relates to the value creation and value capture mechanisms in an ecosystem context. Proper business ecosystem models will be the fuel for organizations across industries to activate optimized processes, promote closer collaboration and improve value proposition. For the applicant for 3D property formation, it is better to generate and submit a property formation model based on an as-built model, or at least in the construction stage.

3) Process: Within 3D cadastral management, there must be an awareness of collaboration enhancement and technical issues during cadastral daily processes, such as lack of unified international standards of cadastral data, as well as 3D data legality, validity, security, interactivity and storage.

4) Technology: Currently, 3D cadastre has no own data structure, which leads to that it cannot define and represent the extent of legal

information in 3D models maturely and reliably. Therefore, to achieve a complete cadastre ecosystem, we recommend to create a 3D cadastral own data hierarchy structure - Cadastral Levels of Detail (CLOD), which is of benefit to represent both legal information, RRRs and geometry information of 3D cadastre. It may address the gap and facilitate the transformations from the hybrid stage towards the full 3D cadastre stage, as well as improve interoperability.

Moreover, how to make 3D models with legal force to register and store the legal information is a practical and essential problem that needs to be solved. 3D PDF may be a transitional way (BIM/IFC models can be exported or converted to 3D PDF) as 3D property formation documents with legal force, which may be easier to be accepted by the cadastral authorities. However, the results of WP1 visualized in 3D PDF showed weak visualization of spaces, compared with BIM/IFC models. Furthermore, development of 3D cadastral index maps rely on the development of semantic 3D city models, where also logical (administrative) spaces are included. This is a new dimension of the 3D city models just added to the internationally leading standard (CityGML) and we can anticipate improvements here the coming years.

5) Business: To make profits and meet the sustainable needs, different actors could initiate and integrate more technologies to create value and accomplish future generations of cadastre such as Internet of Things (IoT), big data, 5G/6G and machine learning.

Given the outline of discussions and recommendations above, continued work could focus on the adoption and implementation of a cadastre ecosystem in connection with 3D urban planning and detailed development plans.

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