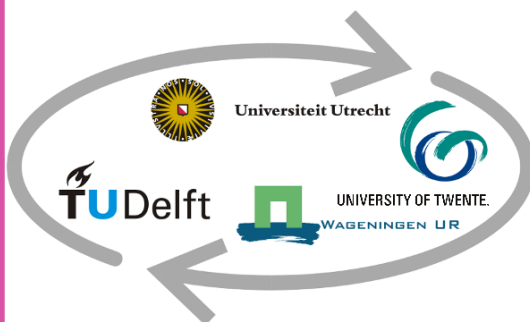


Thesis

BIM/IFC-files as input for 3D Land Administration Systems

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Preface

This research was conducted from September 2020 to November 2021 as a thesis for the GIMA master programme. A full year, working from home because of the Covid-Crisis, I worked on my thesis next to a full-time job which was challenging to say the least. However the subject of this thesis proved to be interesting and motivating to continue the research. The past year I have learned extensively about working with IFC-models, even though it feels like I have just touched the tip of the iceberg when it comes to 3D geographic data and LAS. I hope I can integrate and further develop this knowledge in future work.

I would like to express gratitude to Eftychia Kalogianni, the supervisor of my thesis, who has helped in many ways to complete my thesis. I would like to thank her for her input and inspiration. Even though we have nearly only spoken online, the online appointments were always a good moment to evaluate and think about the next steps. I would also like to thank Peter van Oosterom as responsible professor for this thesis for his input. Another word of thanks goes to Abdullah Kara for his input, and to Menno Mekes and the municipality of Utrecht who provided input in the form of an interview and provided IFC-models for this research.

Abstract

The growth of cities and the pressure on land worldwide leads to more complex and multilevel structures with different space interrelations. For the registration of complex spaces mostly 2D Land Administration Systems (LAS) are used, while a representation of space in 3D could provide a clearer insight. Concurrently, technological advancements rapidly improve methods to collect, create, visualise, register, store and disseminate 3D data. In this context, much research is now being carried out at the sources and data used as input in 3D LAS and the various methods for their collection. In this scene, the approach to reuse data from the design phase is gaining ground. Specifically existing Building Information Models (BIMs), usually encoded in the non-proprietary Industry Foundation Classes (IFC) format (ISO 16739-1:2018, 2018) are considered a promising source for 3D LAS.

Previous research has shown promising results using BIMs as input for 3D LAS. However, the use of IFC-models from practice has not yet been tested adequately. This research investigates the technical issues that are encountered when using real-world IFC-models as input for the registration of apartment rights in a 3D LAS and how that process can be improved. In the context of this thesis, IFC-models are iteratively being validating against technical requirements. Five real-world IFC-models are collected. They are validated on the existence of IfcSpace, the ability to relate the IFC-model to the LAS, the validity of geometries, spatial relations i.e. overlap, and the ability to georeference the IFC-models.

The results of these validation show that the collected IFC-models lack the ability to be georeferenced. Additionally most IFC-models did not contain IfcSpace, or a relation to essential attributes for identifying legal units in the Dutch 3D LAS. Recommendations and guidelines are formulated to address these issues. The IFC-models are placed in a 3D LAS at a conceptual level, in which the legal spaces are enriched with information of the Rights, Restrictions and Responsibilities (RRR's) to those spaces in line with the Land Administration Domain Model (LADM)(ISO 19152:2012, 2012). For this a mapping between IFC and LADM is made.

The results of this thesis include the set of validations and its derived recommendations and guidelines. Additionally a conceptual 3D LAS is made, which consists of a PostgreSQL database, which is LADM compliant, and is visualised in 3D tiles using a Cesium web viewer.

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Acronyms

BIM	Building Information Model	7
LAS	Land Administration System	7
IFC	Industry Foundation Classes	7
RRR	Rights, Restrictions and Responsibilities	8
LADM	Land Administration Domain Model	7
DBMS	Database Management System	13
BGT	Basisregistratie Grootchalige Topografie	18
BAG	Basisregistratie Adressen en Gebouwen	18
LoD	Level of Detail	22
DTM	Digital Terrain Model	27
LCT	Life Cycle Thinking	23
DBMS	Database Management System	13

1 Introduction

1.1 Research Motivation

The growth of cities and the pressure on land worldwide leads to more complex and multilevel structures with different space interrelations. For the registration of complex spaces mostly 2D Land Administration Systems (LASs) are used, while land administration is challenged by an unprecedented demand to utilise space above and below earth's surface. Examples of these are multi-level buildings such as apartments or office buildings, complex structures of buildings with different land ownership above and underground (Janečka & Souček, 2017) and infrastructure above and under the ground and underground utility networks (Stoter & Salzmann, 2003). With growing urbanization and property prices rising, the number of complex structures like these are growing (Shojaei et al., 2013; Stoter & van Oosterom, 2006). Hence, the relationships between people and land in vertical space can no longer be unambiguously represented in 2D, while a representation of space in 3D could provide a clearer insight. Concurrently, technological advancements rapidly improve methods to collect, create, visualise, register, store and disseminate 3D data. The need from the real world to align with technological developments is characterized as one of the key drivers to move towards 3D registrations in Land Administration Systems (LASs).

In this context, much research is being carried out at the sources and data used as input in 3D LAS and the various methods for their collection. In this scene, the approach to reuse data from the design phase is gaining ground. Specifically existing Building Information Models (BIMs), usually encoded in the non-proprietary Industry Foundation Classes (IFC) format (ISO 16739-1:2018, 2018) are considered a promising source for 3D LAS. BIM is widely recognised as a common data environment for 3D life cycle management of buildings. The IFC format and the Land Administration Domain Model (LADM) (ISO 19152:2012, 2012) both are international open standards that have a significant impact in their own domain. Reusing existing models is cost-effective and in line with the Spatial Development Life Cycle (Kalogianni, Dimopoulou, et al., 2020). Previous research has shown promising results using BIMs as input for 3D LAS (Andrianesi & Dimopoulou, 2020; Meulmeester, 2019; Oldfield et al., 2017). However, the use of IFC-models from practice has not yet been tested adequately, as there are various aspects that need to be addressed.

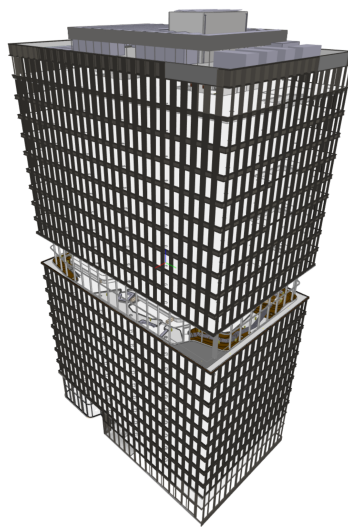


Figure 1: Example of a BIM, the Central Park Building, Utrecht

This research focuses on the challenges that are encountered when using real-world IFC-models for the registration of apartment rights in a 3D LAS and how and how that process can be improved. Legal, organizational and technical challenges from practice are explored, with the focus on the latter. IFC-models are iteratively being validated against technical requirements and placed in a 3D LAS at conceptual level, in which the legal spaces are enriched with information of the Rights, Restrictions and Responsibilities (RRRs) to those spaces in line with the LADM.

It is noted that in this research the term '3D LAS' replaces the term '3D Cadastre' since the first covers both legal and spatial aspects, indicated as Land Registry and Cadastre (Kalogianni, van Oosterom, et al., 2020).

1.2 Research Objectives and Question

This research focuses on the challenges that are encountered when using real-world IFC-models for the registration of apartment rights in a 3D LAS

The main objective of this research is to create recommendations and guidelines for using real-world IFC-models for the registration of apartment rights in a 3D LAS. To realise the research objective, research questions and sub-questions are defined and a methodology is designed to answer them. The research question is formulated as:

How should IFC-models be structured to effectively be reused as input for 3D LAS?

The accompanying research sub-questions will guide the research in achieving the main objective:

1. Which technical, legal and organizational complications are encountered when using IFC-models as input for 3D LAS?
2. Which solutions are recommended for those complications?
3. What are the different interests and benefits of user groups when using IFC-models as input for 3D LAS?
4. Which of the technical complications are encountered when testing real-life IFC-models as input for the Dutch LAS, and how can they be resolved?

1.3 Research Scope

The focus of this research is on investigating the technical issues that arise when using real-world IFC-models as input for the Dutch LAS. The following research boundaries indicate the scope of the study and delineate the subject:

1. To effectively use IFC-models as input for 3D LAS all technical, legal and organizational aspects need to be addressed. Legal and organizational complications will be mentioned to provide a complete picture of the research topic, however they will not be tested or resolved as they are out of the scope of this research.
2. This research focuses on the IFC format. Other 3D - or BIM related models will not be investigated. BIMs can be created with a variety of software and exchanged and stored through a number of formats. However the use of this software is often licensed, and the formats are often proprietary. The most commonly used BIM software include among others Autodesk Revit, Autodesk BIM 360, ArchiCAD and SketchUp (Pro), Tekla Structures and Allplan. IFC is an open format which is supported by a variety of applications, facilitating the exchange of BIMs between

applications. Subsequently, due to the data availability, the IFC format is one of the formats that is the most researched in the literature.

3. For this research real-world IFC-models collected from practice are used, to investigate issues that can occur if a 3D LAS is implemented and IFC-models from practice have to be used. Fictional models will not be tested.
4. This research focuses on the Dutch LAS, hence only IFC-models from Dutch buildings are collected.

Data retrieval has shown to be challenging in this research. Even though IFC-models are used in Dutch practice they are often not open data. IFC-models are obtained by approaching user groups and by using IFC-models which are already obtained for prior research. A number of IFC-models is obtained, however for future research on using IFC-models as input for 3D LAS a broader availability of IFC-models will be helpful in researching a bigger variety of models.

1.4 Research Outline

In the first chapter the problem statement is presented followed by the research question, objectives, scope and boundaries of this MSc Thesis. Chapter 2 describes the methodology according to the design research theory. Chapter 3 consists of the theoretical framework, which provides an extensive literature review on relevant subjects. It describes the concepts and previous research on LAS, LADM, BIM and IFC, while it discusses the challenges described in previous research, as well as the prototypes on which this research is based. It continues with a section which focuses on the environment, being the user groups who deliver input for the requirements for the conceptual 3D LAS. In chapter 4 the development of the prototype is described, including the workflow of the validation of the IFC-models. Chapter 5 presents the results. Chapter 6 contains the evaluation and discussion and lastly the conclusion of this research, where the research questions will be answered.

2 Methodology

To answer the afore-mentioned research question and sub-questions the Design Science Research Approach will be used, since the Build Design Artefacts and Processes are the core of this approach, and it incorporates both practice and theory. Additionally the design cycle is iterative. Feedback from the environment and literature review can be integrated as the prototype is built and evaluated. This chapter starts with an introduction to the Design Science Research Approach (2.1) and continues with the implementation of this method and the corresponding methodological steps (2.2). In 2.2.4 stakeholders are introduced together with the collected IFC-models as case study. Section 2.3 describes the tools (i.e. software) used in this research.

2.1 Design Science Research Approach

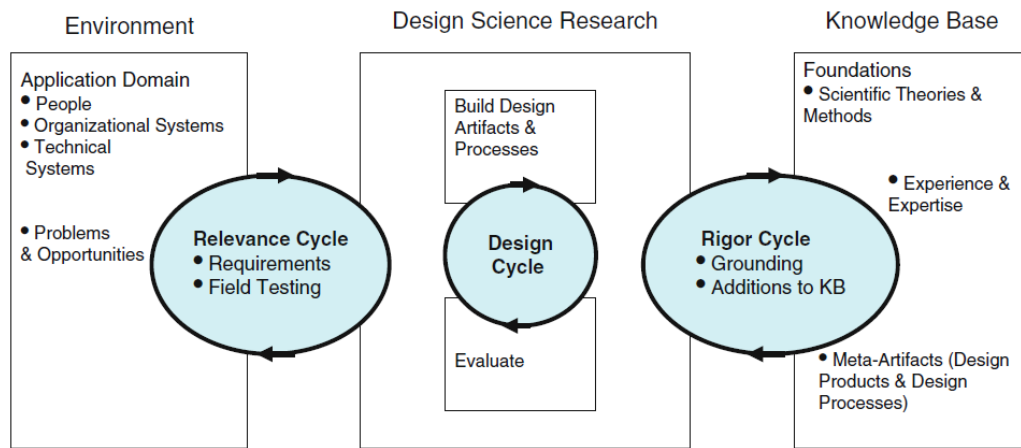


Figure 2: Design Science Research Cycles (Hevner & Chatterjee, 2010)

The Design Science Research approach focuses on the development of 'Artefacts' that solve real-world problems with pragmatism, creativity and innovativity (Hevner & Chatterjee, 2010). Its core is the development of the Build Design Artefacts and Processes, which is continuously evaluated and changed. The Environment and Knowledge Base are input for this Design Cycle (Figure 2).

The input from the environment is based on practice. This includes input from people, organizational systems, technical systems and real-life problems and opportunities. This input is translated into requirements based on experience. Additionally the environments offers input in the form of feedback on the build design and processes through field testing. This cycle is named the Relevance Cycle.

The Knowledge Base consist of input based on theory. It contains Scientific Theories and Methods, Experience and Expertise, and Meta-Artifacts. Thus previous related research and design products and processes provide input for the design. Concurrently it is expected that the Build Design and Processes are adding to the knowledge base, hence introducing new or improved aspects. This cycle is named the Rigor Cycle (Hevner & Chatterjee, 2010).

2.2 Methodological Steps

Based on the Design Science Research approach the following methodological steps are executed in this research (Figure 3). The four main phases of this research are further elaborated at the following sub-sections: First preparation for the research is conducted by approaching stakeholders and collecting data, as well as exploring the tools and data (2.2.1). The operationalization step is described in 2.2.2, and input from the theoretical framework and input from the environment are described in 2.2.3 and 2.2.4 respectively.

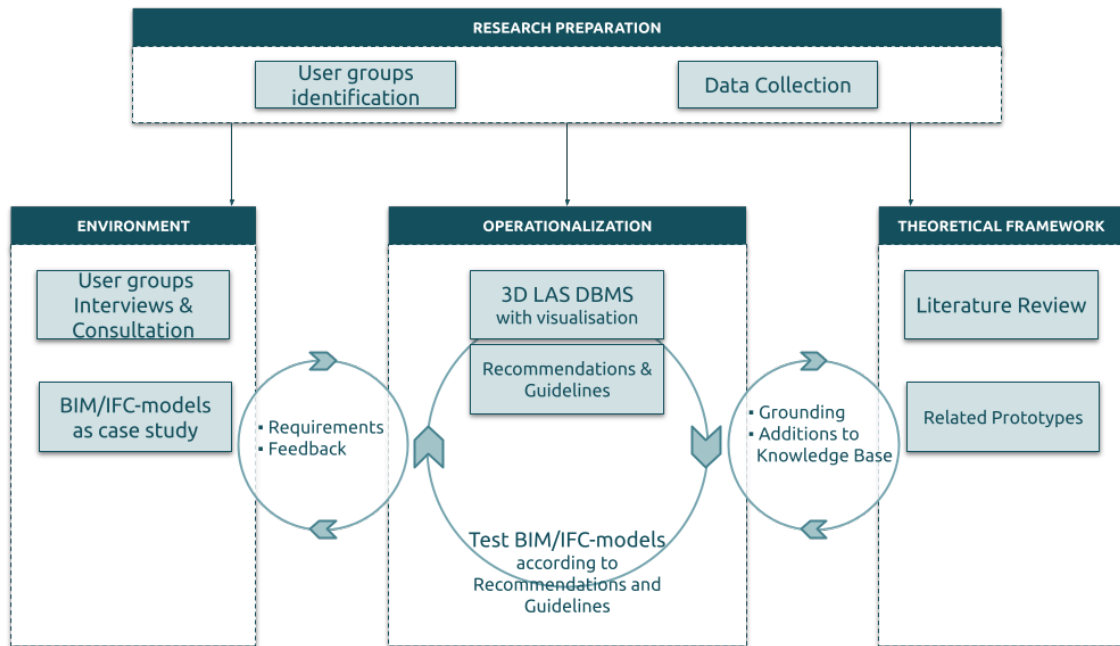


Figure 3: Methodological Steps

2.2.1 Research Preparation

As preparation for the research stakeholders are identified and data is collected. This is done in an early stage of the research as it is known to be challenging to find openly available IFC-models and the models are crucial to the research. Simultaneously contacts are made with designers and users of the IFC-models, whom can provide input for the requirements, as well as give feedback on the prototype, recommendations and guidelines. It is expected that different user groups have different uses for IFC-models, and concurrently different interests and concerns for the use of IFC-models as input for a 3D LAS. The identified stakeholders include architects, as designers of IFC models; municipalities, as they are responsible to collect building drawings for permits, these building drawings can include IFC models, additionally some municipalities are developing digital twins; notaries, as they are involved during property transactions or splitting; the Dutch LAS.

IFC-models are obtained by requesting stakeholders to use their IFC-models for this research. The goal is to acquire a number of IFC-models with a variety of complexity and acquired from various parties, and with a variety of uses, i.e. residential, commercial, offices etc.. To achieve the objective of the research the collected models preferably meet the criteria as described in table 1. It is noted however that due to the expected availability of IFC-models the requirements might not be met for each

collected IFC-model. An overview of the stakeholders approached, and the stakeholders who reacted positively to the request, as well as an overview of the collected IFC-models is given in section 2.2.4.

<i>Concern a building</i>	The IFC-model should concern a building, already constructed or at its design or permitting phase.
<i>Concern a real world IFC-model</i>	i.e. a model which has not been made as fictional example of a BIM-model, but represents a IFC-model which will or has been used in practice, and which is or will be built. This is because this research is focused on the challenges that arise when using real-world models as input for the Dutch LAS as stated in sub question 4
<i>Located in the Netherlands</i>	This research focuses on the Dutch LAS. The Dutch LAS only registers property on Dutch territory, hence the obtained IFC-models shall be preferably on Dutch territory
<i>Have multiple property rights</i>	A benefit of a 3D LAS is that it can represent complex property boundaries. This is not the case when an entire building is one parcel and has one owner, with no disputes of boundaries. A simple free standing house for example does not have to be represented in 3D to make the boundaries clear, a 2D drawing would be sufficient. Therefore it is preferable that the IFC-models contains multiple spaces with multiple owners and various property rights.

Table 1: Requirements For Collected IFC-models

Another part of preparation for the research is initial testing to familiarize with IFC-models, the IFC-encoding and various BIM-software. The collected IFC-models are explored with BIMvision (*BIMvision*, 2021), open source software for viewing IFC-files. With BIMvision the IFC-file structure and attributes are explored.

2.2.2 Operationalization

The operationalization stage of the research consists of defining a set of validation rules and methods to test these rules, defining recommendations and guidelines based on the outcome of the tests, constructing a conceptual 3D LAS and lastly visualize the conceptual 3D LAS. For the operationalization input is used from both theory (theoretical framework) as practice (environment). The methods to collect input from those sources are described in 2.2.3 and 2.2.4 respectively.

Data validation - The collected IFC-models are validated according to a set of validation rules based on input of the theoretical framework and environment. The results of the validations are defined as a positive or negative result. For example, one of the guidelines is that an IFC-model can be georeferenced. A measurable validation consist of the validation of expected needed attributes to georeference the IFC-model. If they exist as expected the result is positive, otherwise the result is negative. If the validation is unsuccessful possible solutions from the theoretical framework or environment are tested and applied

to alter the IFC-models. The tested solutions are added to the recommendations and guidelines, and the IFC-model is validated again according to the recommendations and guidelines. Following the conduction of the validations, the IFC-models that meet the requirements set by the recommendations and guidelines are loaded into the 3D LAS Database Management System (DBMS). Additionally, IFC-models which do not meet the requirements are also loaded into the 3D LAS DBMS, to populate the LAS, as it is concluded that none of the collected IFC-models meet all the requirements and a populated LAS is needed to show the prototype of a LADM based 3D LAS and its visualisation.

This step will answer the fourth sub-question: *Which of the technical complications are encountered when testing real-life IFC-models as input for the Dutch LAS, and how can they be resolved?*

Recommendations and guidelines - The formulation of recommendations and guidelines is one of the main objectives of this research. The recommendations and guidelines describe how IFC-models should be designed in order to effectively be used as input for 3D LAS and accordingly, address the optimal best solution to issues if they occur. The formulation of these recommendations and guidelines are concurrently the answer to the main research question: *How should IFC-models be structured to effectively be reused as input for 3D LAS?*. The initial input for the recommendations and guidelines are known challenges and best practices retrieved from the literature review and requirements stated by the user groups. They are supplemented and adjusted based on the validation of IFC-models. It is noted that the concluded recommendations and guidelines only focus on technical aspects, and are followed with issues that are not yet resolved and need further research.

Conceptual 3D LAS - After the data validation the IFC-models are stored in a conceptual 3D LAS. In the development of a 3D LAS considerations are made regarding the data storage and its visualisation.

The development of the validation rules and validation methods, recommendations and guidelines, conceptual 3D LAS and its visualisation are described in chapter 4.

2.2.3 Input From Theoretical Framework

A literature review is conducted in which previous prototypes, i.e. related work is examined as input for the operationalization stage. Hence the theoretical framework offers the grounding of the 3D LAS DBMS prototype as well as the recommendations and guidelines. Concurrently the results of the operationalization add to scientific research by further developing a 3D LAS DBMS, composing a set of validations, and formulating recommendations and guidelines.

The literature review consists of a review of related scientific work, containing the current status of the Dutch LAS, the ISO19152:2012 LADM standard, BIM and IFC. Concurrently challenges concerning using IFC-models as input for 3D LAS stated in previous research are compiled into a list of challenges in practice. These challenges are categorized into legal, organizational and technical issues. Concurrently, possible solution(s) are listed if they are mentioned in the related research.

By conducting this thorough review the first two sub questions will be answered: *Which technical, legal and organizational complications are encountered when using IFC-models as input for 3D LAS?* and *Which of the technical complications are encountered when testing real-life IFC-models as input for the Dutch LAS, and how can they be resolved?*.

2.2.4 Input From Environment

Stakeholders are interviewed on their experience working with BIM and IFC-models, hence give input for challenges with IFC-models which occur in practice. The given requirements and feedback on the prototype, recommendations and guidelines are iterative and form the relevance cycle. This step will answer the sub-question: *How can the effectiveness of IFC-models as input for 3D LAS be measured for different user groups?*

Several stakeholders are approached, including a notary, a member of the BIM commission of the national organisation for social housing cooperation and employees of the municipality of Utrecht for building permits and designers of a digital twin of Utrecht. The latter replied, and provided IFC-models of Central Park and Westflank in Utrecht. Concurrently he was interviewed. Additionally IFC-models are provided through an architect firm, and virtual systems.

IFC-models as case study

The collected IFC-models are acquired from practice, as described in the data collection section of the research preparation stage (2.2.1; Table 1). They function as case studies for this research. The IFC-models are validated and used as input for the conceptual 3D LAS. Table 2 shows an overview of the IFC-models collected. The IFC-models are further described in this section.

	Name	Supplier	Location
1.	Central Park	Municipality of Utrecht	Utrecht
2.	Westflank	Municipality of Utrecht	Utrecht
3.	Pontsteiger	Menno Mekes	Amsterdam
4.	Schependomlaan	Virtual Systems	Rotterdam
5.	Central Library	Virtual Systems	Rotterdam

Table 2: Collected IFC-models

Central Park and Westflank, Utrecht - The Central Park and Westflank IFC-models (Figure 4) are both part of a development 'cu2030' in the station area of Utrecht. This area is an area of mixed functions as well as different owners. At its core is the Central Station of Utrecht, a transfer hub which is the busiest station of the Netherlands (SpoorPro, 2018). Next to a transport function, other functions include retail, offices, residential as well as leisure.

The largest stakeholders in the area are the municipality of Utrecht, the Dutch railways (Nederlandse Spoorwegen) and Prorail, the railway manager in the Netherlands, but other parties own ground as well. The area is of interest because of the variety in function and owners, as well as the complex 3D structures that are joined with this project. The area is of interest because of the variety in function and owners, as well as the complex 3D structures that are joined with this project. The cadastral map (Figure 5) shows the parcels in the area, of which many are divided because of the multi-level ownership.

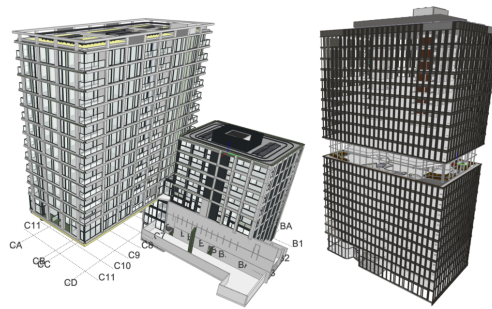


Figure 4: The Westflank (left) and Central Park (right) IFC Models



Figure 5: Cadastral Map of the Utrecht Station Area (geogap, 2021)



Figure 6: Central Park (Middle Building) As Seen From Utrecht Central Station (Own Photo)

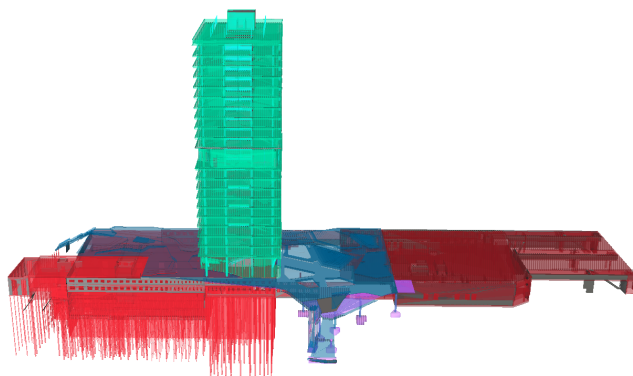


Figure 7: Central Park With Adjacent Models (FME Render)

The Westflank IFC-model contains an apartment building to be built. Central Park contains offices which can be rented. A remarkable feature of this building is the park in the middle of the building, which is to be used as a shared space. The Central Park IFC-model (Figure 6) consists of an aspect IFC-model of the inside and the frontage. Other IFC-models containing stairs to the station area and a parking garage are also collected. They are included for context but are not validated in this research.

It should be noted that both the Central Park and Westflank IFC-model are as-designed BIMs, as both buildings are under construction. For a 3D LAS it is of importance that any adjustments made during construction are implemented in the BIMs, and that as-built BIMs are delivered, so the IFC-models depict the real-world situation.

Pontsteiger, Amsterdam - The Pontsteiger building (Figure 6) has a complex geometry: it contains two towers which are connected through a bridge. It is located in Amsterdam and built in 2015. The building has multiple functions. Apartments are located in the building, as well as a hotel.

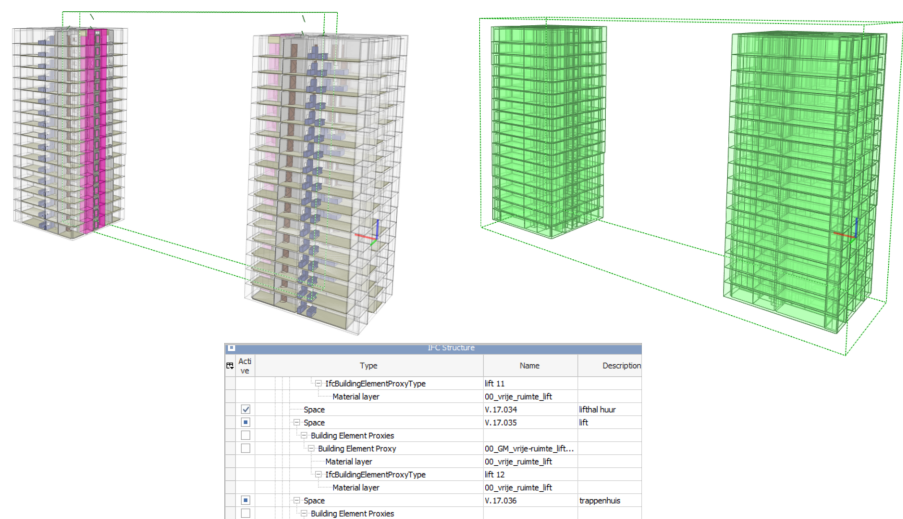


Figure 8: Screenshots of the IFC Model of the Pontsteiger, Amsterdam

Central Library, Rotterdam - The Central Library IFC-model (Figure 9) represents the Central Library in Rotterdam.

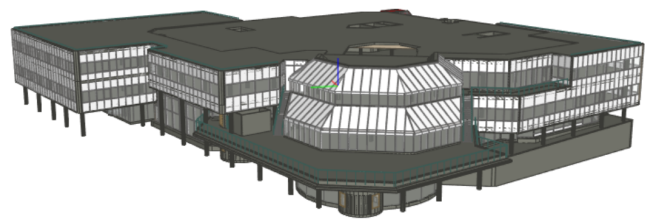


Figure 9: Screenshots of the IFC Model of the Central Library, Rotterdam

Schependomlaan, Nijmegen - The Schependomlaan IFC-model (Figure 10) represents an apartment building in Nijmegen.

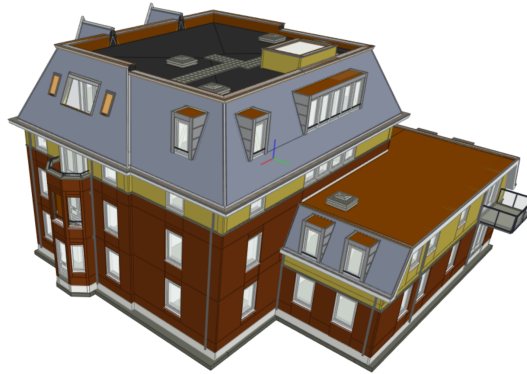


Figure 10: Screenshots of the IFC Model of the Schependomlaan, Nijmegen

2.3 Tools

Various tools are used while carrying out the MSc Thesis:

- BIM-vision is used for investigating the structure, entities and attributes of IFC-models.
- FME Desktop is used to read and validate IFC-models, as well as converting the IFC-models and writing them to the PostgreSQL database and Cesium Tiles. Additionally the IFC-models are affined with FME Desktop to put them in their approximate location.
- AutoCAD Revit is used to explore the IFC-models, as well as generating rooms in the IFC-models where rooms (IfcSpace) was not present.
- PostgreSQL is used to store the data, with the extensions of postgis, postgis topology and postgis sfcgal, to store data, as well as using spatial analysis function to validate the data congruently with FME Desktop.
- PGAdmin is used to access the PostgreSQL database and create additional tables and views.
- Putty is used to make a connection to the remote database.
- Cesium JS is used to view the data.
- IfcGeoRef is used to asses attributes of the IFC-models for georeferencing.
- BIMserver is used to store IFC-models for a file-based approach LAS
- \LaTeX is used to write and format the final thesis.

3 Theoretical Framework

The following sections describe the background of this research. First the definition of LAS is described (3.1), followed by current practice and RRRs in the Dutch LAS (3.1.1) and similar work on the topic of 3D LAS (3.1.2). Core frameworks of this research are described, including the LADM (3.2), BIM (3.3) and IFC (3.3.1). Known challenges from practice are described in subsection 3.4, including legal, organizational and technical challenges. Lastly, Input from the environment, in the form of interviews with two users are described in subsection 3.5.

3.1 Land Administration Systems

Land administration is the process whereby land and the information about land may be effectively managed (UNECE, 1996). It is of essence as ownership of or rights to land provide security of tenure, which allow among others access to food and shelter, effective housing policies and efficient agricultural production.

Land administration consist of land registration and cadastres, where the former concerns the registration of Rights, Restrictions and Responsibilities (RRRs) of land, whereas cadastres register and map parcels. Concurrently land registration is defined as "*the process of recording legally recognized interests [...] in land*" and a cadastre is defined as "*an official record of information about land parcels, including details of their bounds, tenure, use, and value*" (Zevenbergen, 2002). Land registration is thus concerned with the relation of persons to land, in mainly legal aspects. This can be a single person, but also a party, i.e. a government or a company. The relation to the land can be a right, restriction or responsibility. For example the right of ownership, a restriction that the land can not be built on, or the responsibility to manage the environment of the land. Rights can be registered in titles or deeds, which can be accompanied by restrictions, such as a mortgage. Restrictions and responsibilities can be described for the parcel, but can additionally be implied in the law for larger areas or specific land type, and/or can be part of plans of the government, for example the Dutch destination plans (bestemmingsplannen).

Cadastres can have a multi-disciplinary purpose, which are not per definition legal. For example cadastres can also be used to describe land use, soil types and fertility of agricultural purposes. Surveying the land to measure the geometric properties and define the topological relation with other parcels is common (Zevenbergen, 2002).

There is a variety of land administration practices around the world. Some countries only have a land registration, whereas others only have a cadastre. Others combine both land registration and cadastre. The latter combination is a Land Administration System (LAS): a system that both measure the parcels of land and registers the relation in terms of RRR of a party to the land. As previously stated LAS is the definition that will be used since the proposed 3D LAS consist of both the registration of RRR as well as the 3D representation of parcels.

3.1.1 The Dutch Land Administration System

The Dutch LAS, "het Kadaster", consist of both land registration and a cadastre. Formally the Dutch LAS is tasked to acquire, geometrically register, maintain and cartographically visualise public registries. Next to the land administration registry they are also tasked to maintain the registry of large scale geometry (Basisregistratie Grootchalige Topografie (BGT)), the registry of buildings and addresses (Basisregistratie Adressen en Gebouwen (BAG)), registration of underground infrastructure such as cables and pipes, as well as maintaining the net of coordinate points, among others (Kadasterwet, 1989).

This research focuses on the land administration, although it should be noted that the registration of building and addresses (BAG) is related and the registration of underground infrastructure in a 3D LAS could also be of interest, because this infrastructure also has a multi-level component in which infrastructure is layered on top of each other and/or below the property of land not owned by the owner of the infrastructure.

The Dutch LAS has different rights which can be registered, some of which concern multi-level property. First of all the right of ownership (*eigendomsrecht*) indicates the complete ownership of the parcel. This includes in theory not only the land itself, but also the space upwards and downwards from the parcel according to the principle of the rule of accession (*superficies solo cedit*). There are some restrictions to this by the Dutch law, for example there are rules about the airspace for the traffic of airplanes, and rules about the rights to mine. Next to complete ownership, there are forms of limited ownership rights. The right of superficies (*opstalrecht*) allows to own or place immovable property in, on, or under property of someone else. The right of long lease (*erfpacht*) is a right to use the land. The owner of the land, usually a government such as a municipality, provides the land to the owner of the long lease in exchange for a one time cost or returning costs. The building on the land is the property of the right holder. The right of easement (*erfdienstbaarheid*) is a right of which the owner has to allow access to his land to serve another actor. A common example is the right of way, which allows a right-holder of a neighbouring parcel to use the land of a parcel to gain access to a public road or other property. The apartment right (*appartementsrecht*) is a right to a part of a split parcel, usually vertically. This right is used for multi-level apartments. Since 2D parcels do not define exclusive ownership of apartments, the ownership of a residence in an apartment building is required to have the boundaries of properties in a deed of division (*splitsingsakte*), part of this deed is a 2D drawing with a graphical representation of the boundaries (Figure 11). Joint ownership (*mandeligheid*) is the shared ownership of property usually on the boundary of the parcel, for example a wall or fence on the boundary of parcels (Stoter et al., 2013).

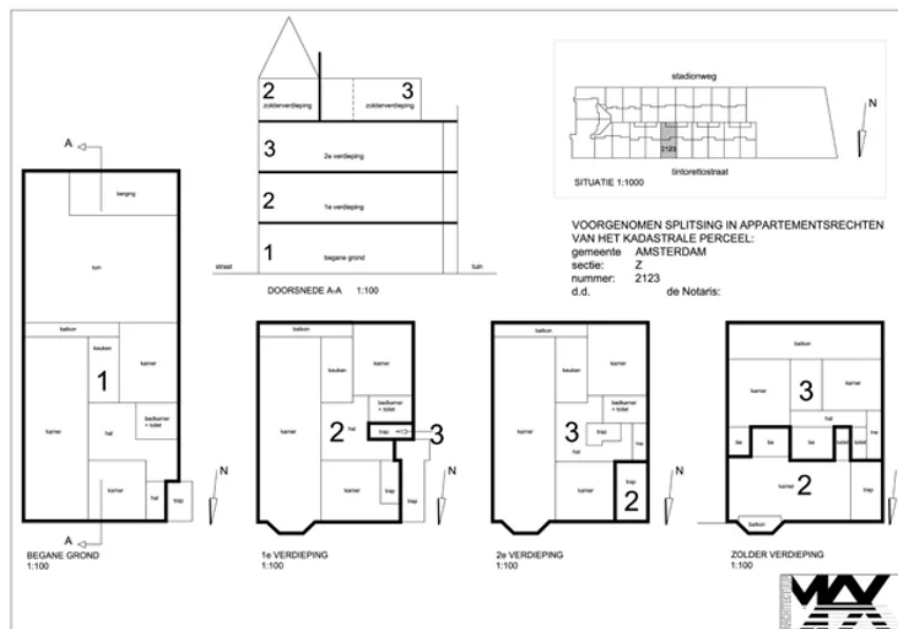


Figure 11: Example of a *Splitsingstekening* (Division Drawing)

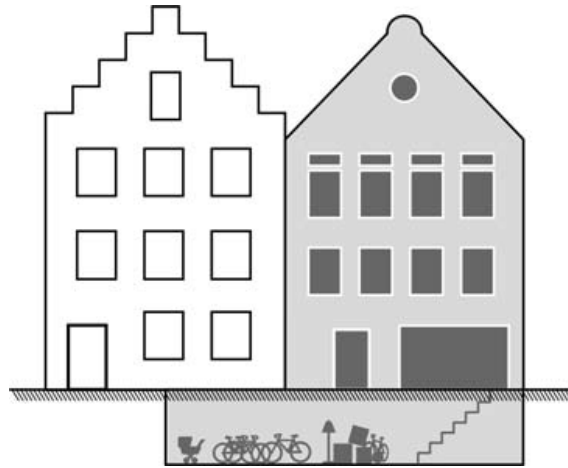


Figure 12: Example of the rules of Accession, In Which The Owner Of The Grey Building Also Owns the Cellar Which is Under the White House (Stoter, 2004)

Even though rights are not registered in 3D, some of the limited rights allow for a division of rights in 3D situations. The apartment right being the most apparent, as it deals with vertical split property. In addition to these rights the principles of vertical and horizontal accession (*vertikale en horizontale natrekking*) apply in the Dutch LAS. This principle defines the ownership of a property when it is part of, and can not be divided, even though it may be on, go over or under the ownership of some one else. This principle applies on all parcels, i.e. a house is part of the property as it is on the owned land. But it also applies in multi-level property, i.e. a cellar under a house (figure 12). Other examples of horizontal and vertical accession are tunnels, bridges and underground infrastructure.

The representation of parcels in 2D maps in case of multi-level property which overlap, is handled by dividing the map into multiple parcels, of which for each parcel the multiple rights are represented. Even though this representation might be clear for the people who are involved in registering the property, it is hard for people who are not familiar with the real-life situation to interpret these maps. An example of a complex 3D situation represented on a 2D map is the Unilever building as shown in figure 13.

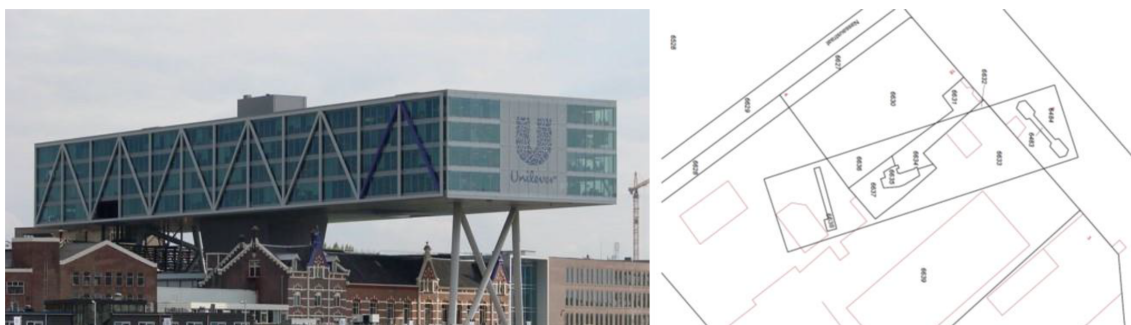


Figure 13: The Unilever Building and Its Representation on a 2D Parcel Map (Stoter et al., 2013)

3.1.2 Developments Towards 3D LASs

In the Netherlands, research has been conducted on the possible layout of a LAS in which 3D representations can be incorporated. Stoter et al. (2016) implicated a 3D model of the train station in Delft to be registered in the Dutch LAS. A 3D pdf is added as a division drawing, instead of a 2D drawing. The 3D representation is added in the existing LAS and legal framework. This model contains multiple spaces with different parties and RRRs, which can be queried in the 3D pdf. The use of a 3D representation allowed for a better presentation of a 3D complex situation, however, the 3D representation cannot be linked to surrounding parcels. Cemellini (2018) developed a system architecture prototype for a 3D LAS, which focused on 3D data storage, dissemination and visualisation through a web-viewer. It is extended by Meulmeester (2019), who researched the possibility of IFC-models as input in a 3D LAS, enriched with legal information required by the Dutch LAS (Figure 14). However this has not been tested with real-world IFC-models.

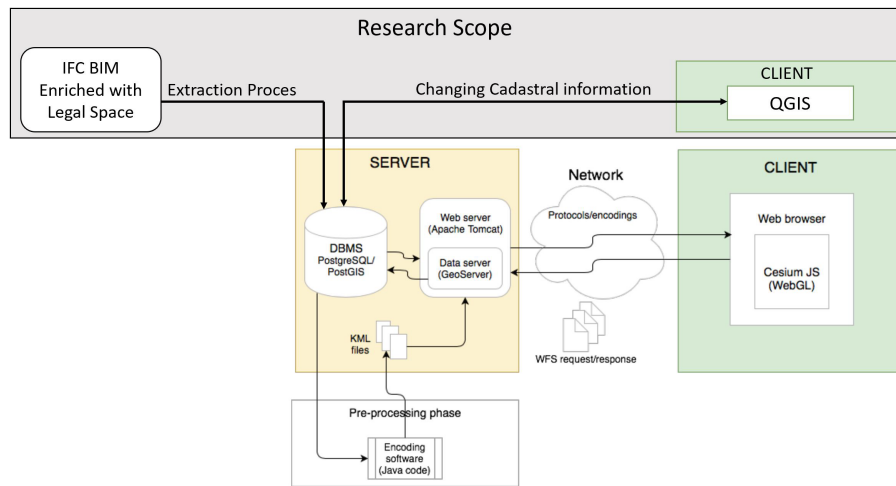
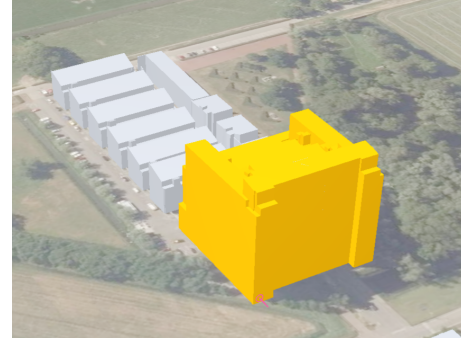


Figure 14: System Architecture of 3D LAS DBMS Prototype of Cemellini (2018) Extended By Meulmeester (2019), (Meulmeester, 2019)

Other research explores the possible input for 3D LASs. As acquiring 3D data can be costly, research focuses on using existing data formats as input for 3D LASs. Sun, Mi, Olsson, Paulsson, and Harrie (2019) proposes a framework for integrating BIM with cadastral information, where both an IFC-model and CityGML model were stored in a LADM database. Barzegar, Rajabifard, Kalantari, and Atazadeh (2021) proposed a schema for a 3D LAS in which 3D spatial queried can be performed. A IFC-model is validated and linked with legal data. Meulmeester (2019) enriched a IFC-model with legal data as a property set and transferred it into a conceptual 3D LAS. In doing so he investigated the requirements needed for IFC-models to be defined as legal spaces for the Dutch LAS. Atazadeh et al. (2017) built a prototype model for 3D LAS with input from IFC-models and explores the storage of legal property in IFC-models. Oldfield et al. (2017) researched the possibility of using BIM as input for 3D LAS and proposed the use of IfcSpace as legal space and IfcZone for grouping spaces into legal zones. Another research which investigates the use of BIM for a 3D LAS is from Olfat et al. (2019) in which a workflow is proposed to share, document, visualize, analyse, interpret, and reuse 3D land administration data throughout a buildings life cycle. IFC-models are enriched with legal information using property sets.



(a) Studentcomplex Cambridgelaan, Utrecht



(b) Its Representation in the 3D BAG

Figure 15: Comparison of a Building With a Bridge and Its Representation in the 3D BAG

Recently the Dutch LAS published a 3D base registry (3D basisvoorziening), generated from the BGT and BAG. However this is not a replacement of the cadastral base registry, or the BGT and BAG. Even though the representation has a Level of Detail (LoD) of 2.2, not all buildings are correctly presented, for example when the building is inclined and has a bridge 15. In addition buildings as a whole can be queried, but not individual parcels, i.e. an apartment in an apartment building can not individually be queried.

The prototype of this research will be based on previously built prototypes of Cemellini (2018) and Meulmeester (2019). The reason to further built on these prototypes is that they are concerned with the same conditions as this research, i.e. the Dutch LAS, LADM compliant, and using IFC-models as input.

3.2 Land Administration Domain Model

The LADM is an international knowledge domain specific standard capturing the semantics of the Land Administration Domain. It provides a common, standardised, global vocabulary, ontology and semantics aiming to stimulate the development of software applications and accelerate the implementation of land administration systems that support sustainability objectives (van Oosterom & Lemmen, 2015). The LADM is a conceptual model and one of the first spatial domain standards within ISO TC211, aiming to support “an extensible basis for efficient and effective Land Administration Systems” (Kalogianni, van Oosterom, et al., 2020). Currently the development points for the LADM are modelling, storing, visualising, maintaining spatial units; LA as part of chain spatial development activities, no isolation; Interoperability with other standards; Use in spatial development chain (BIM cycle). The LADM has a wide use and interest, with several countries investigating and/or applying LADM in their LAS (Kalogianni et al., 2018). For example Croatia (Mader et al., 2018), Malaysia (Hassan et al., 2008), China (Ying et al., 2018) and Israel (Adi, Shnaidman, & Barazani, 2018).

Figure 16 shows the UML model of LADM, which consists of three main packages. The party package (green) consist of classes which represent a party, which can be a person or organization such as a municipality or a company. This can also be a group of parties. The administrative package (yellow) store the Rights, Restrictions and Responsibilities (RRRs) to a basic administration unit (BAUnit). They are also linked to the party who has the RRR. A basic administration unit is zero or more spatial units, i.e. parcels. The BAUnit is linked to the spatial unit package (blue) which contain classes to store spatial information of the BAUnit. This can be a verbal description, a 2D map, and also a 3D model, among others. To support the spatial unit package for storing geographical information, the representation and survey package (red) contain classes to store surveying and other geographical data.

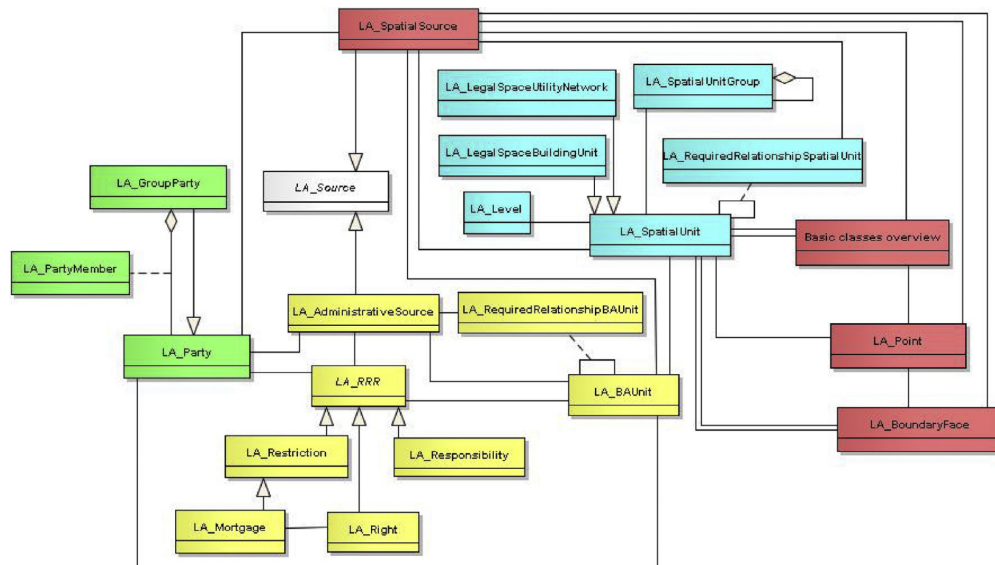


Figure 16: Land Administration Domain Model (Lemmen et al., 2015)

3.3 Building Information Models

The concept of Building Information Models (BIMs) is about storing and maintaining data in the form of a 3D model through the entire life cycle of a building. For this purpose BIMs contain both 3D spatial information (geometry), as well as semantic information about the building (Kalogianni, Dimopoulou, et al., 2020). It fits with the principle of Life Cycle Thinking (LCT), which focuses on the collaboration between parties and the reuse of sources. The collaboration of different parties in the design stage of a BIM can prevent building mistakes by using clash detection, hence combining models of different disciplines and notice if there are overlaps between objects which cannot exist in real-life. Detecting these clashes in the design phase prevents the costs that occur when these mistakes would be noticed in the building phase.

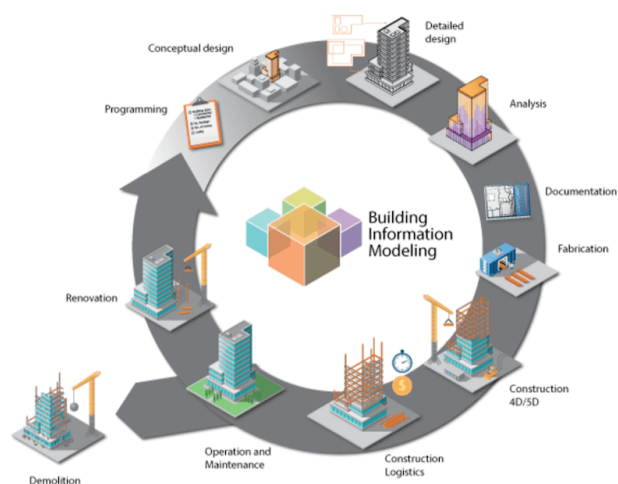


Figure 17: BIM Cycle (*What Is BIM*, n.d.)

However the circular approach does not stop after the designing phase, as BIM can be used during maintenance, renovation and demolition as well. Hence BIM can be used from the design, through maintenance, through possible renovation, until the demolition phase (Figure 17). Concurrently BIM could be used for permitting buildings, as well as register 3D spatial units with related RRRs in LAS. Kalogianni, Dimopoulou, et al. (2020) argues the registration of a building in the LAS is vital in a buildings life cycle, as "Such cooperation is expected to enable new ways of data harmonisation and use in this complex environment, to improve efficiency of design and data acquisition, to improve data quality (in relation to specific regulations), to minimise inconsistencies, data loss, mismatch and overlap between the various stages, and to enhance data re-use from design phase to end user and registration/operation phases".

3.3.1 IFC Encoding

BIMs can be designed with a variety of software. This allows for different stakeholders to maintain a work flow with software suitable for their purpose. To exchange BIMs in a non-proprietary format the Industry Foundation Classes (IFC) file format is used. This file format is maintained by BuildingSmart. Its data schema (Figure 18) consist of entities and layers containing both spatial, organizational and administrative attributes.

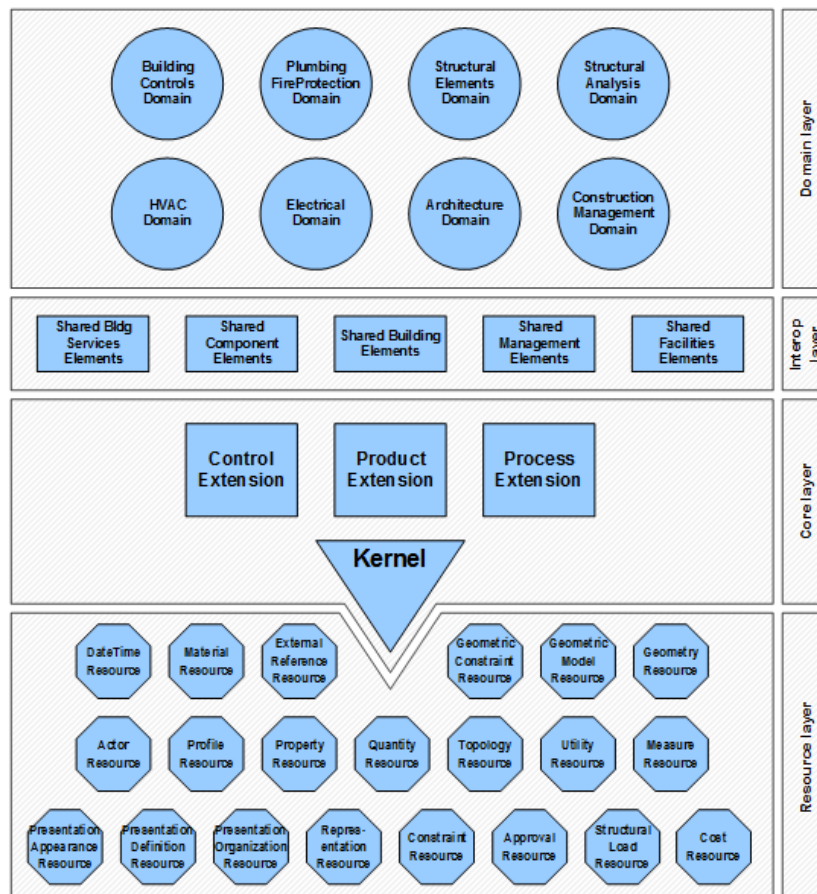


Figure 18: Data Schema Architecture of IFC (ISO 16739-1:2018, 2018)

3.4 Challenges In Practice

For the implementation of a 3D LAS, challenges are known to arise. These challenges can be categorized into legal, organizational and technical issues. Legal challenges are issues which concern the registrations of RRRs of 3D parcels. For example, the possibility to register property boundaries in 3D. Organizational challenges concern the parties and people involved with LASs. These include the institutions who regulate and implement LASs, and the stakeholders involved. Technical challenges are issues concerning data capturing, dissemination, databases, visualisation, as well as interoperability issues. For example, data-interoperability, faulty, outdated or incomplete datasets, georeferencing, data storage, data dissemination and visualisation are some of the technical issues that are known to arise (Aien et al., 2011). The following subsections address the most dominant legal, organizational and technical challenges for the implementation of a 3D LAS.

3.4.1 Legal Aspects

Legal aspects contain the challenge that arise for the legal registrations of RRRs of 3D parcels in a LAS.

Legal status - The foremost question is how to give a 3D LAS a legal status. The presentation and storage of parcels in the Dutch LAS is in 2D. The question is thus whether and how a 3D representation can have the same legal status. For example, does a digital file have the same status as a paper document? Do all parties agree on the boundaries as presented in the 3D representation? The challenge is thus to obtain a legal status for parcels in a 3D LAS (Stoter, 2004).

Privacy - Another challenge is privacy. A LAS registers information about people, which is privacy-sensitive data. In the Netherlands these are protected under the General Data Protection Regulation (GDPR) or better known in Dutch as the Algemene Verordening Gegevensbescherming (AVG). Even though the Dutch LAS does distribute personal data on request, since the interest in transparency for the real estate market is above the interest in privacy in this regard, it is not open data. Concurrently this data can be requested but may not be used for charitable or commercial goals, i.e. requesting a list of addresses and market to those addresses. Hence in a 3D LAS confidential information is stored but should be protected and only available on request. The challenge is then how to handle and protect the confidential information in a 3D LAS (Larsson, Paasch, & Paulsson, 2018).

Defining common space - The current laws of joint ownership and apartment rights deal with common space. A 3D LAS should have the same option to register and disseminate common space. The question arises then if and how the information of shared properties should be acquired and stored. In IFC-models rooms can be defined (as IfcSpace). The objects between or outside those rooms however are not defined as rooms (i.e. IfcSpace), such as walls, slabs and slats. They could be extruded and defined in a 3D LAS, yet then it should be defined which objects can be defined as shared property, and concurrently the number of objects stored in a 3D LAS will effect the amount of data stored. Concurrently some spaces like stairwells and entrance halls can have a defined room, yet the challenge is then how to formulate the RRR's of all parties to that common space.

Copyright - The creator of 3D data has intellectual property of the data, and as such there can be copyright on the data which prevents free re-use (Larsson et al., 2018). The challenge is how to incentivise designers of IFC-models to distribute their models as open data, or distribute them free of charge to the authorities that need to process the data. Alternatively, who should pay for the copyright of the IFC-models. This low availability of open IFC-models is additionally an impediment in the research to use IFC-models as input for 3D LAS.

3.4.2 Organizational Aspects

Organizational aspects contain the challenges that arise for the parties and people involved with LASs.

Standardisation - There is no standard practice amongst organizations to define 3D parcels and their linked RRR's in the Netherlands. This leads to multiple solutions, which notaries have to judge as valid or invalid, and which of that information to include in the deed (Stoter, 2004). In addition, even though there are guidelines on best practice for designing BIMs, as described by the Dutch BimLoket in BIM Basis ILS and by BuildingSmart, these are not mandated and not always followed. The challenge is which standards should be used and what elements these standards should consist of for designing input for 3D LAS as well as requiring a legal parcel for a 3D LAS. In addition a challenge is how these standards can be enforced.

Mandate - Changes are required in the government processes, stakeholders involvement and surveying industry processes. To make these changes a mandate is needed, there has to be a political will and need in society to shift to a 3D LAS (Shojaei et al., 2018).

Planning - (Shojaei et al., 2018) argues that a 3D LAS is technologically possible, however, such a development needs to be planned and needs a roadmap. A shift towards a 3D LAS faces a variety of challenges as described in this chapter, concurrently many stakeholders from different backgrounds are involved. Planning and creating a roadmap, as well as agreeing on the right steps to take and the order of steps, is an organizational challenge.

Funds - Costs have to be made to acquire data and make an organizational shift to mandate the (re)use of 3D data (Larsson et al., 2018). The challenge is where to acquire those funds. A political choice can be made to invest in a 3D LAS, or commercial parties can invest when they see an added market-value. In any case, the incentive of providing the funds is needed.

Change in workflow - The implementation of the LADM in existing LAS is a foundational change, according to Kalantari et al. (2015). Concurrently the registration of 3D parcels is an impactful change as well. The implementation will alter the workflow of a variety of parties.

Data Loss - In some cases data is designed or collected in 3D but transferred and stored as 2D data (Larsson et al., 2018). This might have a organizational cause, i.e. the workflow in data storage is to store data as 2D, or there is no mandate to save data in 3D, or a technical cause, i.e. the systems are not capable of handling 3D data. The challenge is to find the cause and take away the impediments that hinder 3D data storage.

3.4.3 Technical Aspects

Technical aspects contain the challenge that arise with the collected data format, i.e. IFC-models, and challenges with i.e. data storage and dissemination.

Data Storage - A technical issue is the question how data is stored. The decision on how to optimally store data is dependant on a number of factors, i.e. the usage of data, the amount of users, hardware and software available. For example a project developer may require multiple aspect models with a high level of detail which translates to a bigger file size, to oversee the to be build object and be able to perform clash detection. A project developer may also prefer cloud storage for associates to cooperate, but does not necessarily need to store the IFC-models in a DBMS or relate the model to other models. Whereas the designer of a digital twin might prefer a lower level of detail, and the need for a DBMS and lower file size in order to efficiently disseminate the data in an online viewer. Hence there is not a one-fits-all solution for how to best store 3D data. Hence when designing a 3D LAS an appropriate system architecture has to be defined. This includes decisions which hardware and software to use, as

well as a data model which can be queried effectively, a solution for data dissemination etc. (Stoter, 2004).

Data dissemination - related to the challenge of how to store data in a 3D LAS is how to disseminate the data. (Cemellini, 2018) lists requirements for a 3D LAS viewer. These include navigation tools and views controls, with which a user can interact in the 3D LAS viewer by zooming, panning, rotating and tilting. Another function is a tooltip function, to view the attributes related to the 3D object. To place the 3D object in its context integrating topography and reference objects is needed. Reference objects can be Digital Terrain Models (DTMs), 3D buildings models and infrastructure networks. To show the interior of a building, transparency in the viewer is needed. Other methods to better view objects also can be included, such as a wireframe view, explode view, sliding view and/or a cross-section view. Object selection and an object search function is also of importance to search and select a specific object. A 3D measurement tool can be included to measure objects, including its area and volume.

Level of detail - BIM provides an information model for many different uses. Because of this, a model usually is detailed and inclusive of many objects. The question arises if all the objects should be contained and visualised in a 3D LAS. Both out of a purpose-viewpoint; is this information needed, as a technical viewpoint. The amount of detail impacts the size of the database and concurrently the loading time (Sladić, Radulović, & Govedarica, 2018). The challenge is which level of detail to use, a choice which influences the data storage. Concurrently, a challenge is how to deal with models with a different level of detail. This can pose a challenge especially when the boundaries of two concurrent models have to be defined, but the models have a difference level of detail. If they overlap how should this difference be balanced and registered? (Larsson et al., 2018)

Legal spaces - A IFC-model exists of multiple entities, including semantic entities, as well as building element entities, i.e. IFC wall, IFC slab etc. The IFC space entity is used to represent rooms. These rooms can be used to represent 3D parcels, i.e. legal space (Cemellini, 2018; Meulmeester, 2019). However the IFC space entity is not always included in IFC-models.

Relation to the LAS - To be linked with the Dutch LAS, (3D) parcels require to be uniquely identified according to the current Dutch LAS. Meulmeester (2019) proposed a propertyset for IFC-models to include the unique identifiers required by the Dutch LAS, i.e. indexnumbers. However, a technical challenge is how to implement this propertyset in a standardized way, and how to validate these propertysets.

Valid geometries - The geometries in IFC-models require to be valid. Since during the calculations of spatial relations between geometries, invalid geometries can result in errors or an incorrect calculation. Additionally invalid geometries can result in errors in the visualisation.

Spatial relations - Property should be mutually exclusive, thus properties should not overlap. In addition gaps inside a model should be avoided. This is true for concurring models, but also for space inside the models, especially when there are multiple owners. To check for overlaps a 3D LAS should have topological support, so that spatial analysis, such as an overlap analyses, can be performed. (Cemellini, 2018).

Georeferencing - There are a multiple of definitions of georeferencing. In the context of BIM/GIS data integration Zhu and Wu (2021) defines georeferencing in the context of BIM/GIS integration as "the process of establishing spatial reference for BIMs so that they can be managed and analysed in a GIS after their local coordinate system is transformed into a proper coordinate reference system." (p.17). in the context of this research this definition is adopted. The placement of parcels in a 3D LAS have to reflect the position of the real world. Hence, the relation of the parcel to the world,

and additionally the relation to other parcels is of importance. However IFC-models are designed in local coordinate systems, rather than each point reflecting the real coordinate in a coordinate reference system (CRS). BIM/IFC-files do contain reference point to EPSG: if this is defined by the designer. From those points the coordinates of the model can be derived, so that it can be placed in context of a CRS, and additionally other models. In other words IFC-models can be georeferenced. This is however known to be challenging. In this regard a differentiation is made in the version of the IFC file. For georeferencing IFC files, in the IFC4 file format the entity *IfcMapConversion* is introduced which facilitate coordinate transformation hence subsequently georeferencing. However the georeferencing capabilities of IFC2x3 are known to be far less sufficient (Zhu & Wu, 2021). Zhu and Wu (2021) also notes that FME does not always handle georeferencing IFC-files correctly, for example when deriving the angle.

3.5 Environment

The expected users of a 3D LAS include the public, land registries, land surveyors, notaries, AEC industry, urban planners, local government, real estate agents, contractors, banks, valuers, engineers who issue permits and architects among others (Kalogianni, van Oosterom, et al., 2020). Experience from practice is discussed with an architect and an employee of the municipality of Utrecht who is contributing to a digital twin of the municipality of Utrecht.

From the interviews carried out with various user groups it has been concluded that they experience a hurdle of the reusing of IFC-models after the building was built (as stated by the designer of Pontsteiger case study). In the experience of the architect the BIM is not maintained after the building phase, which contradicts the life cycle thinking of BIM. For example in a digital twin in the city of Amsterdam, the city in which the Pontsteiger building is built. The 3D model used in the digital twin is created from an extrusion of the BAG, and thus represented as a box, which differs from his design. Another example of data loss mentioned is that a BIM is supplied to a municipality or other organization, but the workflow of that organization is based on 2D data. Concurrently, the BIM is transposed to 2D data, and the original 3D data is not maintained, hence not reusable. 3D models of surrounding buildings are often used in the designing phase of new buildings, especially when designing high-rise in urban environment. Studies are made to assess the wind flow of the current and to be build buildings, as well as sun studies to assess the expected shadows of the building and its surroundings. These 3D models of surrounding buildings can be made with extrusions of 2D building maps, however an architect in this stage would benefit from accurate existing 3D models.

The employee of the municipality of Utrecht, who developed a digital twin, mentions that even though he sees an added value of adding IFC-models to the digital twin, a conversion is required to simplify the model. This is needed to decrease the file size, but also to reduce the level of detail, as the level of detail in IFC-models is often not wanted for a digital twin. However conversion, i.e. simplifying IFC-models is time-consuming, as hardly any model is built the same and thus requires manual labour to adjust to make the model suitable for a digital twin. Hence he would benefit from designers adhering to standards to be able to automate the process of simplifying IFC-models for input in a digital twin.

4 Development of Prototype

This chapter describes both the development of the set of validation rules that have been executed in the context of this research, as well as the architecture of the 3D LAS at a conceptual level. The workflow to combine these parts of the prototype are depicted in figure 19. First, the IFC-models are validated using a combination of FME Desktop Workspaces and functions of the PostgreSQL PostGIS and SFCGAL extensions. If the result of a validation of an IFC-model is negative, possible solutions to remedy the issue are explored and applied if possible. After the validation, IFC-model are uploaded to a PostgreSQL Database. All IFC-models are uploaded, however its should be noted that if this workflow would be applied in a real-world 3D LAS only IFC-models which have a positive result on all validation tests should be accepted.

Views are constructed for the contents of the PostgreSQL database, to disseminate the data needed for the visualisation. This includes the 3D geometry, as well as the LADM attributes, containing information about the parties, RRR's, and Building Units. The view is converted into 3D tiles using FME Desktop. The 3D tiles are transferred to a remote server. A web page containing Cesium web viewer is used to visualise the 3D tiles. The web page is styled using CSS and Java.

First, the set of rules and its methods for data validations are described (4.1.1, Thereafter subsection 4.2 describes the development of the conceptual 3D LAS, including considerations and a comparison between file-based and database-based storage (4.2.1), the relation of the 3D LAS and the LADM (4.2.2) and the development of the visualisation of the 3D LAS (4.2.3).

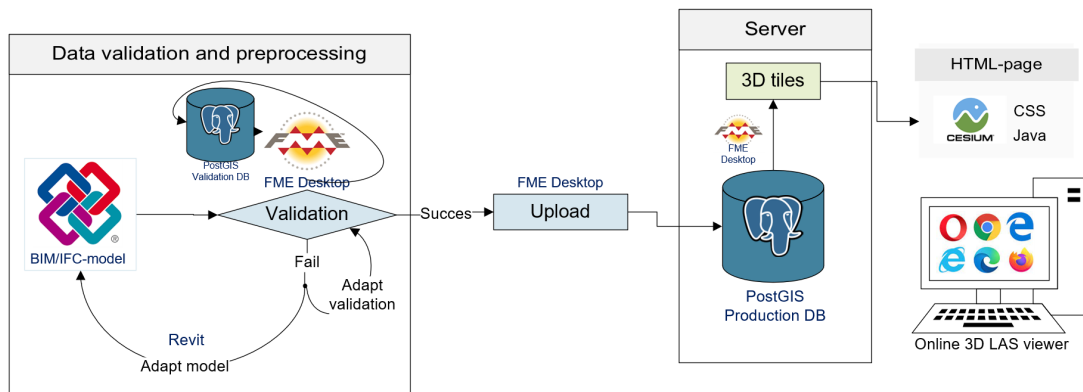


Figure 19: Data Flow of Prototype

4.1 Data Validation

This subsection describes the set of validation rules, as well as the methods used to test the collected IFC-models. The rules that are stated below, are based on the literature review and the study of IFC models:

1. The availability of legal spaces, including the representation of rooms as `IfcSpace`, to define legal units which can be linked to the RRRs of the legal unit (4.1.1).
2. The ability to relate the legal spaces to the LAS (4.1.2).
3. The geometries to be valid (4.1.3).
4. The `IfcSpace` volumes to contain no overlaps or gaps, as spaces should be mutually exclusive (4.1.4).
5. The ability to georeference the IFC-model, as the geographic location of a building is necessary in the context of a LAS (Cemellini, 2018; 4.1.5).

4.1.1 Validation of Legal Spaces

For the input in a 3D LAS a IFC-model has to contain uniquely identifiable `IfcSpace` entities which represent rooms. These rooms can be grouped to form a unit, this definition should be stored in the IFC-model. Rooms can be defined in IFC-models as `IfcSpace` entities. However, the presence of `IfcSpace` in a IFC-model is dependant on if the designer included it or not.

The first step in the validation of legal spaces is to check if `IfcSpace` entities are present. The outcome does not inform whether the `IfcSpace` is a complete set of all rooms. This is validated through the overlap/gap analysis (4.1.4). Conclusively checks are made on the presence of `IfcSpace`, these are integrated in a FME workspace (Appendix A).

4.1.2 Validation of Relation to the LAS

IFC space volumes have to be uniquely identifiable so that they can be linked to legal building units, additionally they can be grouped into legal units, i.e. an apartment which consists of multiple rooms. The former is checked by validating the existence of a `IfcGloballyUniqueId` (`GlobalId`). For the grouping of rooms there are no mandated standards. Meulmeester (2019) proposed the addition of a `propertyset` to `IfcSpace` to include the Dutch LAS indexnumbers etc. (Table 3), however this proposal has not been implemented in standards. Additionally groups of rooms can be defined by groups in the model, such as `IfcZone`. Lastly a relation between rooms can be implied by the name of spaces, i.e. spaces which belong to the same apartment have the same prefix.

IFC Entity Type	LADM
<code>IfcPropertySet</code> : apartment number	<code>LA_SpatialUnit</code> , <code>LA_BAUnit</code>
<code>IfcPropertySet</code> : space type	<code>LA_BAUnit</code>
<code>IfcSpace</code> : <code>IfcGloballyUniqueId</code>	<code>LA_LegalSpaceBuildingUnit</code> , <code>LA_BAUnit</code>
<code>IfcSpace</code> : geometric representation	<code>LA_LegalSpaceBuildingUnit</code>

Table 3: Proposed Property Set and Its Mapping to LADM (Meulmeester, 2019)

The validation of an integrated relation to the LAS is done in a FME Workspace (Appendix A). It is validated by inspecting the IFC-model whether: `IfcSpace` contains a `propertyset` which contains

attributes required by the Dutch LAS; groups of rooms are defined in the model; a relation between rooms is implied in the name of `IfcSpaces`.

It should be noted that next to the rooms, a legal unit contains the interior building elements, and often the exterior elements adjacent to the rooms. Current practice in the Dutch LAS do not model the boundaries, such as walls and floors, as property. The reason for this is that the graphical representation, a 2D drawing of the building, is not legally binding. Rather it is a graphical representation of the building and where the building is located. Therefore the modelling of building elements such as walls and floors is not possible for the Dutch LAS, and only the rooms are defined as legal units (Meulmeester, 2019).

If a LAS does allow building elements to be modelled as property, it should be defined in the IFC-model to which legal unit they belong. When these links are not integrated in the IFC-model, some links can be calculated by adjacency to a legal unit. Interior elements, such as walls dividing two legal units, however result in a conflict. Hence to define the ownership of building elements manual adjustments might be needed. Alattas et al. (2021) describe the process of subdividing a building with its building elements into private, common, and exclusively common spaces. The latter can be used to describe building units between two legal units, which cannot be defined as shared or common space of all right holders in a building, but are related to only the right holders or legal units adjacent to the building element.

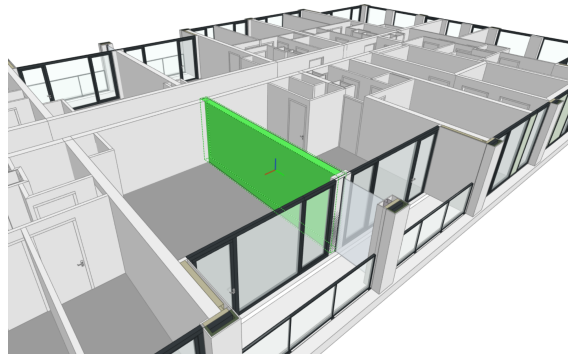


Figure 20: Example of a Shared Building Element in The Westflank Model

4.1.3 Validation of Geometries

For testing the validity of geometries in the IFC-model it is assessed whether the features of the IFC-model are compliant with OGC 1.2.0 (Yutzler, 2018). When calculating spatial relations between objects, invalid geometries may result in errors or an incorrect calculation. Therefore the geometry of features is validated using a FME Workspace (Appendix C).

Where `IfcSpace` is present it is checked if there are no geometric errors in the volume. Basic integrity validations are performed to check if: a feature contains -0, NaN, or Infinity; contains Null geometry parts; contains degenerate or corrupt geometries. Additionally it is validated if a surface of a solid self-intersects in 2D, if there are no non-planar surfaces, invalid solid voids, invalid solid boundaries (i.e vertices not used, not enough faces, face wrong orientation, not a valid 2-Manifold, surface self intersects, surface not closed, surface wrong orientation).

4.1.4 Validation of Spatial Relations

It was assessed whether the IfcSpace volumes do not overlap. For the Dutch LAS, parcels have to be mutually exclusive. Hence overlap between parcels is not allowed. The touching of geometries is expected, as two adjacent spaces can touch on the bounding surface. Figure 21 shows possible DE-9IM relations for 3D geometries. For the Dutch LAS spaces have to be mutually exclusive, hence geometries may not equal or overlap each other, since that contradicts the premise of legal units being mutually exclusive.

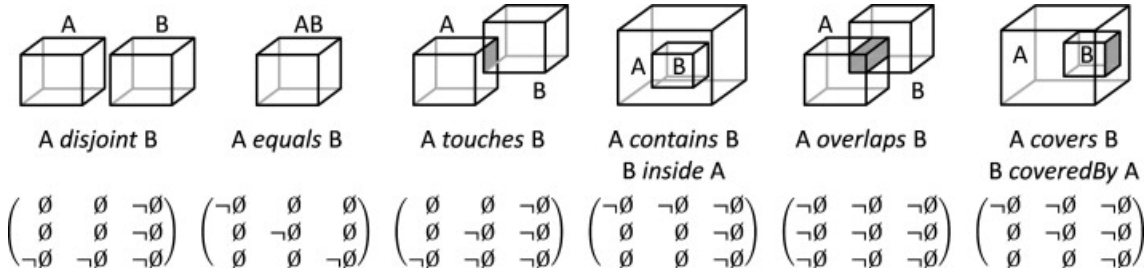


Figure 21: Eight Predicates Defining the Possible Topological Relationships Between Two Solids in 3D (Daum & Borrmann, 2014)

Defining spatial relations between 2D geometries is well integrated in the used software. FME Desktop and PostgreSQL with the extension of PostGIS have tooling to create a DE-9IM matrix which represents the spatial relation between 2 geometries. However this tooling is not yet able to deal with 3D geometries. Collection of polygons, i.e. a geometrycollection or multi-polygon, can be used as input, however the outcome still represents the 2D relations, not taking into account a Z-coordinate.

For validating whether there is overlap a method is used which utilises the ST_3DIntersection function of the SFCGAL PostgreSQL extension (Postgis.net, 2021). This method extracts the shared portions between two 3D geometries (Figure 22). However touching surfaces are also extruded. To exclude these false positive results, surfaces (geometries with a 0 volume) are excluded and not counted as overlap. The geometries are compared to each other using a materialized view. The query does not utilize a spatial index, which has a negative impact on the execution time. Concurrently only geometries which have a distance of less than 10 meters are compared. The outcome of the materialized view is analysed within FME Desktop (Appendix B).

```
SELECT concat(t1.globalid , t2.globalid) AS id_comb ,
       t1.globalid AS gid_1 ,
       t2.globalid AS gid_2 ,
       t1.basename ,
       st_3dintersection(t1.geom, t2.geom) AS intersectgeom
FROM "LA_LSBU" t1
CROSS JOIN "LA_LSBU" t2
WHERE t1.globalid <> t2.globalid
AND t1.basename::text = t2.basename::text
AND st_3ddistance(t1.geom, t2.geom) < 10::double precision
AND geometrytype(t1.geom) IS NOT NULL
AND geometrytype(t2.geom) IS NOT NULL
```

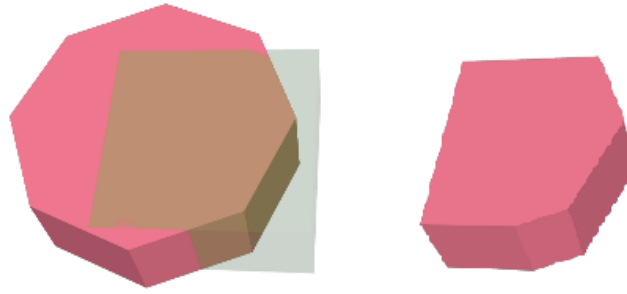



Figure 22: Result of the ST_3DIntersection Function, With 2 3D Geometries as Input (Left), and the Resulting Volume (Right)

4.1.5 Validation of Georeferencing

IFC-models are nearly always designed in local coordinate systems (LCS), rather than coordinate reference systems (CRS). Hence, to georeference a IFC-model to the correct location a transformation has to be made and stored in the model. The process of georeferencing exists of two steps. First spatial reference is established and secondly coordinate transformation parameters and transforming coordinates are obtained. With these components an object can be georeferenced. The spatial reference information of IFC-models can be embedded in the model. For IFC4-files, the entity `IfcMapConversion` can be used, which contains the attributes Eastings (E), Northings (N), OrthogonalHeight (O), XAxisAbscissa (XAA), XAxisOrdinate(XAO), and Scale (S), from which a transformation matrix can be derived (Figure 23).

$$[x' y' z'] = [x y z] \times \begin{bmatrix} S \times \cos \theta & S \times \sin \theta & 0 \\ -S \times \sin \theta & S \times \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} + [E, N, O],$$

Figure 23: Transformation Matrix Derived From `IfcMapConversion` (Zhu & Wu, 2021)

In IFC2x3-files however, this entity is not yet available. Spatial reference information can be embedded however in other entities. In `IfcGeometricRepresentationContext`, an attribute of `IfcProject`, the two attributes `TrueNorth` and `World Coordinate System` contain spatial information. `TrueNorth` represents the true north of the model. `World Coordinate System` is referring to the engineering coordinate system, rather than what in most GISs is defined as WCS, i.e. a EPSG like WGS84. When this is not set it refers to the local point (0,0,0) (Zhu & Wu, 2021).

Spatial reference points can be stored in `IfcSite`, containing the attributes `RefLongitude`, `RefLatitude` and `RefElevation`, which give reference points opposed to the local (0,0,0)-point as WGS84 coordinates in degrees, using the EPSG 4326. This reference point is expected to be the real location of the origin point of the IFC-model. Another indicator of the locations of the model is in the address attribute.

LoGeoRef	Supported CRS	Storing Entities
<i>LoGeoref10</i>	No CRS, approximate location by means of the address.	IfcPostalAddress referenced by either IfcSite or IfcBuilding
<i>LoGeoRef20</i>	WGS84 EPSG:4326	Attributes RefLatitude, RefLongitude, RefElevation within IfcSite
<i>LoGeoref30</i>	Any Cartesian CRS, including projected coordinates (CRS not specified in the file)	IfcCartesianPoint referenced within IfcSite (defining the projected coordinates of the model reference point); IfcDirection attribute of IfcSite.
<i>LoGeoref40</i>	Any Cartesian CRS, including projected coordinates (CRS not specified in the file)	Attribute WorldCoordinateSystem storing the coordinates of the reference point in any Cartesian CRS (including the projected ones) and direction TrueNorth.
<i>LoGeoref50</i>	Specific projected CRS, specified by means of the EPSG code	IFC v.4 only 3. Coordinates of the reference point stored in IfcMapConversion using the attributes Eastings, Northings and Orthogonal-Height for global elevation. Rotation for the XY-plane stored using the attributes XAxisAbscissa and XAxisOrdinate. The coordinate reference system (CRS) used is specified by IfcProjectedCRS in the attribute Name by means of the proper EPSG code.

Table 4: Synthesis of LoGeoRefs as Defined By Clemen and Hendrik (2019), Adjusted From Noardo et al. (2021)

Clemen and Hendrik (2019) give an overview of the different ways to store the afore-mentioned attributes, which facilitate the georeferencing a IFC-model. It should be noted that the existence of these attributes are dependent on whether or not the designer included them in the model. Additionally, the latter LoGeoRef50 is based on attributes which are introduced in IFC 4, whereas older models, including the ones validated in this research, are IFC 2x3 and do not support these attributes.

The IFC-models are validated by investigating the existence and contents of the attributes stated by Clemen and Hendrik (2019; Table 4). The tool IfcGeoRef (Clemen & Hendrik, 2019) is integrated into a FME workspace (Appendix A), and is used to assess the georeferencing capabilities of the IFC-models. For each IFC-model it is assessed if it complies with LoGeoRef10 to LoGeoRef50, and if so the contents of the attributes are exposed. For georeferencing a IFC-model to the 3D LAS, preferably LoGeoref50 is present, although this is only expected in IFC 4 models. For correctly georeferencing IFC 2x3 models, either LoGeoref30 or LoGeoref40 has to be present.

4.2 The 3D LAS Schema at a Conceptual Level

In the conceptual 3D LAS both geometric and semantic information about the buildings need to be stored. For the geometry, it is important to convert the IFC-models to a format which can be visualised. The semantics have to include attributes with information about parcel identification, its RRRs and parties involved. For this, a mapping from IFC attributes is made to integrate the LADM classes (4.2.2). First, considerations for the data storage are elaborated upon in the following subsection.

4.2.1 File-based vs Database-based Storage

Two main approaches can be followed to store data: file-based and database based. The former is based on files, i.e. a server or hard drive where IFC-models are stored. In a database based system, IFC-models are loaded into a Database Management System (DBMS). For LAS, the Dutch LAS uses a DBMS, as do most LAS to register property. However, designers of IFC-models can be used to a file-based system. A comparison is made between the two approaches (Table 5).

For filesystems, the user requires knowledge of the software in which the file is opened, but does not require knowledge about a DBMS. For example, an architect knows how to navigate to and alter BIM in a filesystem, but may need extra training to receive the same data in a DBMS. In addition, DBMS

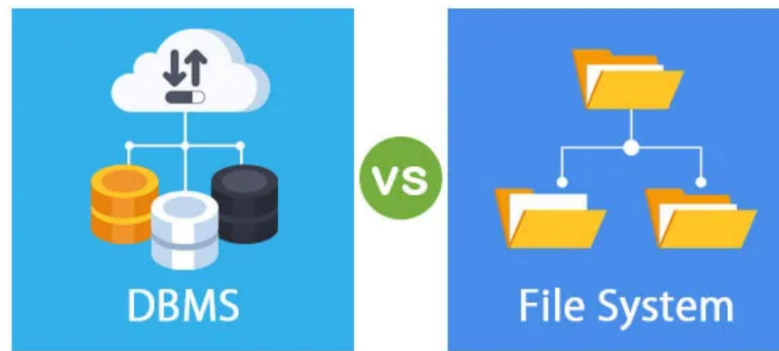


Figure 24: DBMS vs File System (Educba, 2021)

store data at a more abstract level (Logothetis, Valari, Karachaliou, & Stylianidis, 2018). However, this can be resolved by allowing applications to query and alter the DBMS, so that knowledge about the DBMS is only needed by the DBMS manager.

In file systems, usually each applications has its own proprietary files, which may not be opened by all software. An advantage of a DBMS is that data can be accessed through multiple applications, for example by querying the data. Additionally data can be shared from the DBMS as a service, i.e. an API or WFS (Logothetis et al., 2018). In concurrence with the shareability of data, in file systems files can be duplicated and altered, and therefore have a greater risk of data inconsistency. In a DBMS this inconsistency is avoided by allowing multi-use of data (Logothetis et al., 2018). For storing data, a DBMS offers the ability to enforce constraints, i.e. the restriction of a data type, or formatting in a column. File systems do not offer this option, although software can also have built-in constraints for data. Regarding security, DBMS offer built-in backup and security capabilities, in contrary to file systems.

For the storage of IFC-models, there is no fit-for-all solution. A decision had to be made based on the usage, size and wanted performance of data. Also, it should be noted that the pro's and cons listed might not apply to all DBMS and file systems, and that some forms in between exist. There are some considerations to be made for IFC-models specifically. IFC contains many related entities. Storing them in separate tables results in a complex DBMS structure. A challenge is how to store IFC efficiently in a DBMS without losing qualitative data, i.e. attributes (Xu, Huang, Li, Li, & Li, 2018). Another consideration is the usability, dependant on the user group, users can have a known workflow based on a file system or DBMS. The conversion between data types also have to be considered. IFC-models can be stored as-is in a file system. However for the insertion into a DBMS a conversion has to be made. A possible solution for this is to include the file, i.e. in a blob which allows the storage of unstructured data in a DBMS. And/or a link to the file in the DBMS. This allows for the advantages of the use of a DBMS in LAS, without losing any qualitative data of the IFC-models.

File-based approach - For the file-based approach, the collected IFC-models are stored in a BIM-server. BIMserver stores IFC-models as objects, and allows for data querying, versioning and model checking amongst others. For this purpose, a BIMserver is installed on a local server.

DBMS approach - First, a PostgreSQL database is set up on a remote server. The extensions PostGIS and SFGCAL are included in the database, to support the storage of geometry, and spatial functions. Database management is done in PGAdmin, for the creation of views and materialized views. The insertion of IFC-models into the database is done using a FME Desktop workspace (Appendix C). The IFC entities project, site, building and buildingstorey are stored in separate tables, to avoid

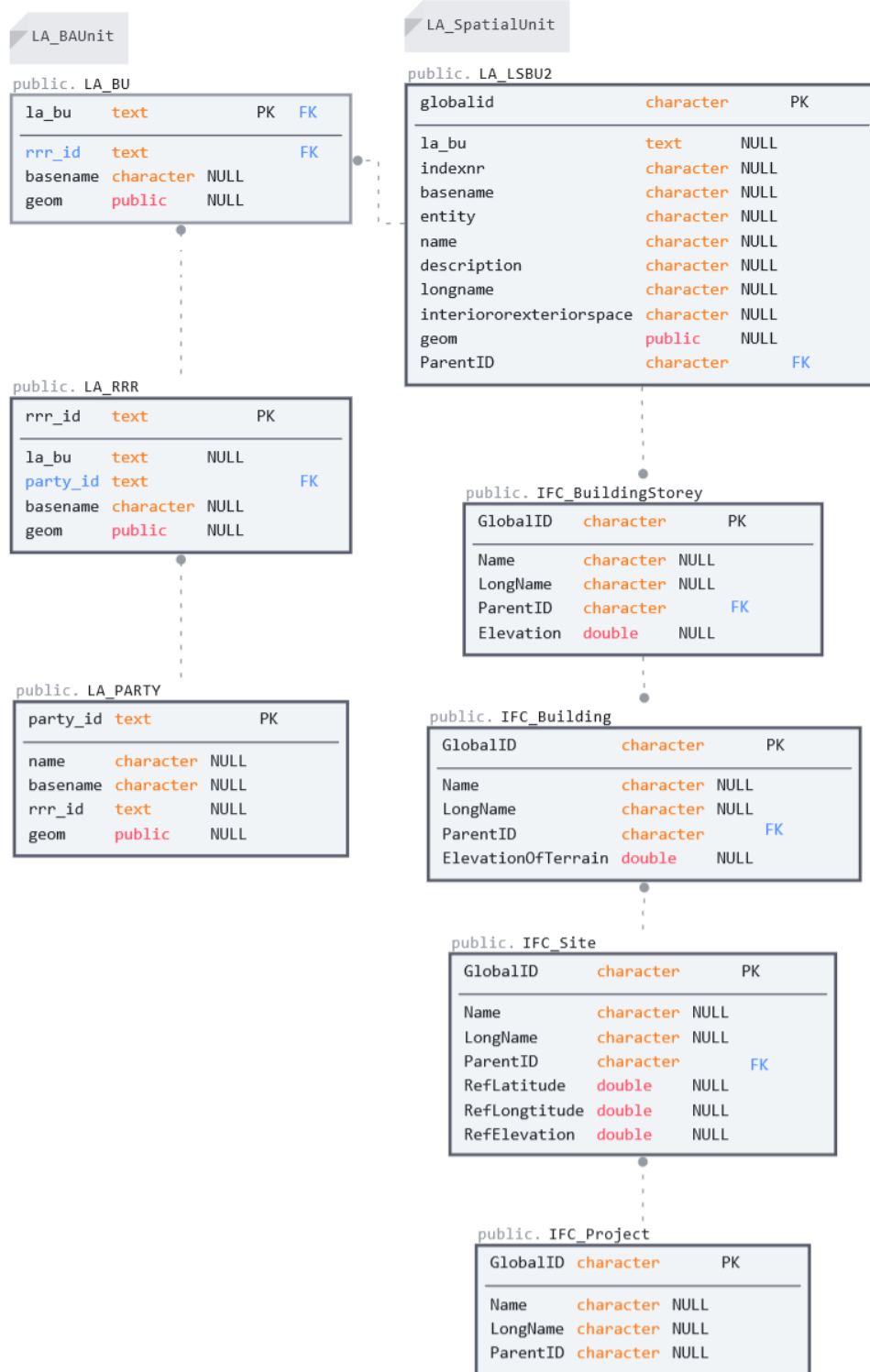


Figure 25: Database schema

	File system	DBMS
<i>Usability</i>	User requires knowledge on how to use the software in which the file is opened	User requires DBMS knowledge, or a GUI to represent/edit data
<i>Sharing</i>	Often one-use application	Multiple applications can access data simultaneously
<i>Data consistency</i>	Inconsistency can occur	No duplicate data
<i>Data integrity</i>	No constraints are enforced	Integrity constraints can be enforced
<i>Recovery</i>	No integrated backup	Integrated backup
<i>Detail</i>	Detailed data representation and storage of data	Abstract view of data (dependant on the DBMS design)

Table 5: Comparison Between File Systems and DBMS

storing these attributes for every instance of *IfcSpace*. By relating the created tables based on their *GlobalId* and *ParentGlobalId*, the inserted IFC-models can be queried based on the *IfcProject*, *IfcSite* etc. (Figure 25).

4.2.2 Relation of the 3D LAS to the LADM

The prototype is based on the ISO 19152 LADM. Only parts of the LADM are modelled to show the basic framework of LADM and the possibility to integrate the IFC-models into a LADM based DBMS. The 3D LAS DBMS can be extended with the entire LADM framework. It should be noted that none of the IFC-models contain information about the parties or type of rights. In order to showcase a possible implementation and the link of the 3D LAS with the LADM, fictive instances for *LA_BAUnit*, *LA_Right*, and *LA_Party* are generated in a FME Desktop Workspace (Appendix D).

The prototype includes the classes *LA_SpatialUnit*, *LA_BAUnit*, *LA_Right*, and *LA_Party*. *LA_SpatialUnit* contains the volumes. The *IfcSpace* volumes extracted are used as *LA_SpatialUnit*. Next to the *GlobalId* as a unique identifier of the IFC-model, an *indexnumber* for the Dutch LAS is added. The *indexnumber* contains a unique identification as used by the Dutch LAS. *LA_BAUnit* refers to zero or more spatial units, and is used to group spatial units. For example when multiple spaces belong to the same parcel. *LA_Right* contains information about the type of right. It should be noted that this could also be extended with *LA_Responsibility* or *LA_Restriction*, under the *LA_RRR* class. *LA_Party* contains information about the party which is related to the *LA_Right* and the *LA_BAUnit* (Figure 25).

A validation database is made which contains one table, which can be populated with *IfcSpace* from a IFC-model temporarily to validate the model. Materialised views are made which execute the function for overlap and intersection. This is a separate database, as the models should be validated as correct input before inserting them into a production database.

4.2.3 Development of 3D LAS Visualisation

Viewing the geometric contents of the PostgreSQL database can be done in multiple ways. This subsection describes the explored possibilities to visualize the contents of PostgreSQL database, including methods to view the database locally, and thereafter how the contents can be shared, disseminated and visualised on the internet. Optimally the DBMS can be assessed through the internet, so that it is

accessible for every one, without the use of other software. However the local options are discussed as they can be used during the development of the 3D LAS.

PostGIS itself cannot represent 3D geometry without a plugin. Only 2D geometries are represented. A plugin for viewing X3D geometries is available (robe2, 2021), but this was not further explored in this research. FME Data inspector can be used to view the database locally. A database connection to the database is needed. Even though FME Desktop can visualise 3D features, its options for transparency are suboptimal, as they show distortion.

QGIS also can be used to view the database locally. To do this a connection with the database is made. There are a few impediments when viewing 3D models with QGIS however. First of all the CRS of the map has to be a projected CRS, secondly a 3D symbology has to be applied and the 3D viewer has to be added, and lastly the biggest impediment: QGIS cannot apply transparent symbology to 3D models. The last impediment hinders the view of volumes which are obstructed by other spaces and concurrently in the overlap and intersection view it is harder to distinguish the features.

To disseminate the 3D LAS DBMS in an online viewer it is preferred that the viewer has a direct connection with the DBMS, hence when the database is updated this is directly visible in the viewer. However there is not yet a current practice to connecting and viewing 3D DBMSs. Several options are explored.

Firstly a common used way to disseminate geographic objects from a database to an online viewer, is to use geoserver. Geoserver is an application on top of Apache Tomcat on a server. It connects to a PostgreSQL database and can disseminate this data in the form of a Web Feature Service (WFS) or Web Map Service (WMS), which can be loaded into an online viewer. Geoserver is installed on the local server, however although it can disseminate 2D geometries, it is more challenging for 3D geometries. An impediment is that to disseminate 3D data through the geoserver, the geometries should be converted into an open 3D geometry format such as KML, or CityGML. These formats however have their own specifications, hence the PostgreSQL tables have to be transformed into those formats, but this requires a mapping from IFC to the specified format. An attempt is made to transfer a model into the CityGML format and KML format. However the result of this transformation could not be validated, thus not be disseminated, as a valid file. Hence the approach of using Geoserver requires IFC-models to also be validated correctly as either KML, CityGML, b3dm, or another format. Additionally, it should be assessed if transferring IFC-models to PostgreSQL to file-formats which can be disseminated through Geoserver is a viable workflow.

Another approach to disseminating the contents of the PostgreSQL database is to convert them into 3D tiles. This can be done with an FME workspace or pg2b3dm. pg2b3dm is a tool that converts 3D geometries from PostgreSQL to b3dm tiles (Geodan, 2021). The transformation is like a transformation from PostgreSQL to 3D tiles in FME. A benefit is that it is open source software which can be run from the command line, making automation possible. A disadvantage of converting the contents of the PostgreSQL database to 3D tiles is that it requires an additional action. This poses a risk that whenever this action is not done congruent with a database update, the visualisation of the database does not show the most recent, i.e. current situation (Chen, Shooraj, Rajabifard, & Sabri, 2018). A benefit of this approach is that 3D tiles are smaller in file-size and quicker to load.

For the visualisation 3D tiles are chosen. Cesium is used as a viewer to display the 3D tiles. For the production database views are constructed to represent all attributes for a spatial unit in one row, enriched with information of the IFC-model. The view Cesium_view contains information about a spatial unit, its right, the party to the right, and the project name, building name, indexnumber and geometry of the IFC-model. This view is used in the 3D LAS viewer.

```

SELECT sp.indexnr AS la_legalspacebuildingunit ,
       sp.basename AS ifc_file ,
       sp.longname AS space_longname ,
       bu.la_bu AS la_buildingunit ,
       rrr.rrr_id AS la_rrr ,
       pr.party_id AS la_party ,
       pr.name AS party_name ,
       sp.geom
FROM "LA_LSBU2" sp
JOIN "LA_BU" bu ON sp.la_bu = bu.la_bu
JOIN "LA_RRR" rrr ON bu.la_bu = rrr.la_bu
JOIN "LA_PARTY" pr ON rrr.rrr_id = pr.rrr_id ;

```

The 3D tiles are uploaded to the remote server, so that when the tiles are updated no change in the code for the viewer has to be made. Although this requires more manual action, this can potentially be minimized as the FME workspaces do allow for automation through FME server. FME Server is software in which workspaces built in FME Desktop can be run. Additionally these workspaces can be run per a users request online, without the user having to own or code in FME Desktop. An example of this would be a validation server in which the user uploads a file and sees the validation results based on the output of one or more FME workspaces. With FME server multiple workspaces can be run parallel or subsequently, allowing a workflow of multiple workspaces which are running subsequently based on the output of the former workspace. Automations in FME server make it possible to start of workflow of workspaces triggered by an event. This event can be amongst others user input, but also a update in a database. FME server is licensed and has not been used since it has to be installed on the localhost of the server. However, FME server could potentially add value to the workflow based on the built workspaces in this research.

5 Results

A set of validations is carried out on the 5 collected real-world IFC-models(5.1), the results are presented in Table 6. Based on the outcome, recommendations and guidelines are formulated (6.2.1). The IFC-models are put into the conceptual 3D LAS and visualized in a web-based viewer (5.2)

BIM/IFC-model	IFC version	a) Legal Spaces					b) Valid Geometries				c) Overlaps	d) Georeferencing				
		Contains IfcSpace	Unique GlobalId's	LAS propertyset	Groups	Implied relation in name	OGC pass	Passed	Repaired	Failed	Overlaps	LoGeoRef10	LoGeoRef20	LoGeoRef30	LoGeoRef40	LoGeoRef50
1. Central Park	2x3	No	Yes	No	No	No	100%	97%	3%	>1%	-	False	True	True	False	False
2. Westflank	2x3	No	Yes	No	No	No	100%	80%	20%	>1%	No	True/False	True	False	False	False
3. Pontsteiger	2x3	Yes	Yes	No	Yes	Yes	100%	96%	4%	>1%	Yes	True/False	True	False	False	False
4. Schependomlaan	2x3	Yes	Yes	No	No	Yes	100%	84%	16%	>1%	No	True/False	True	False	False	False
5. Central Library	2x3	No	Yes	No	No	No	100%	97%	2%	1%	No	True/False	True	False	False	False

Table 6: Results of Validation

5.1 Results of Data Validation

5.1.1 Legal Spaces

In 2 out of 5 IFC-models IfcSpace is present (Table 6 - a). The Central Park, Westflank and Central Library model do not contain IfcSpace. Revit is used to automatically generate rooms in the IFC-models with no IfcSpace. However not every room is recognized, and some building elements such as columns, or incorrectly defined as room. For example in the Rotterdam library model only the staircases are recognized as rooms. In the Westflank model, not every room is recognized either, however small beams which are not occupiable are defined as room (Figure 26). In the attempt of trying to add rooms to the Central Park model the hardware used to export the adjusted model to IFC failed as it took too much processing space.

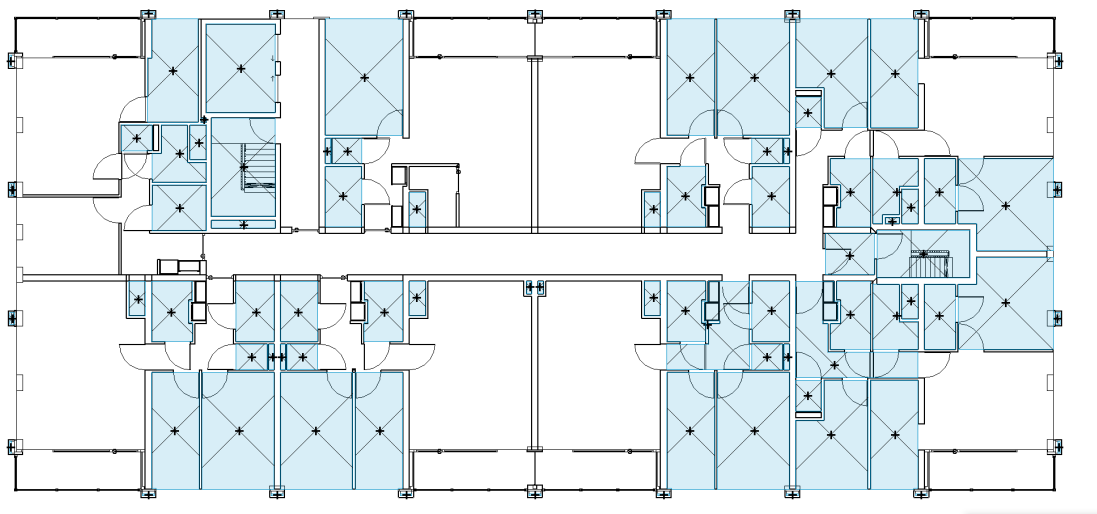


Figure 26: Automatic Space in Revit (Light Blue), Westflank

5.1.2 Relation to the LAS

The Central Park, Westflank and Central Library models contain no information required for the Dutch LAS. The Schependomlaan model contains names of rooms which imply a relation. The rooms contain a numbering, i.e. 1.00, 1.01, 2.00, 2.01 etc. However this is not relatable to the Dutch LAS. The Ponsteiger model contains no information such as a LAS index number either, but groups are defined which represent legal units, such as 'bnr. 100'. Conclusively the lack of IfcSpace in some models, and lack of Dutch LAS information are insufficient for placement in a Dutch LAS.

5.1.3 Geometries

All geometries of IfcSpace, i.e. legal spaces, in the IFC-models are compliant with OGC 1.2.0. (Table 6 - b) Only in a few geometries multiple non-planar surfaces and incorrect oriented geometries were detected, these are triangulated and repaired.

5.1.4 Spatial Relations

For the Pontsteiger model, overlap is present. This is due to the grouping of spaces, in which the group of spaces is also defined as a space, which overlap with the containing spaces. In the Westflank model the 3D intersection function resulted in a collection of geometries, however none of them contained any volume, i.e. they represent surfaces, which indicates a touching relation between two adjacent geometries. No overlap is found in the Central Park of Central Library model, however none to only a few rooms are present in those models. The Schependomlaan model contained no overlap either, although it should be noted that not all IfcSpace geometries could be correctly extracted.

5.1.5 Georeferencing

An analysis is done through the IfcGeoRef tool to assess which georeferencing attributes the IFC-models contain (Table 6 - d). LoGeoRef10 information is present in 4 out of 5 IFC-models, however in these attributes, IfcPostalAdress, incomplete or incorrect addresses are stated. All IFC-models contain Reference points according to LoGeoRef20. These include RefLatitude, RefLongitude and RefElevation which reflect a single reference point in the WGS84 (EPSG:4326) CRS. However these points do not reflect the actual location of the buildings. For example, the Ponsteiger reference point is in Canada. The Central Park, Westflank and Central Library models all contain a reference point close to, but not exactly at the real location of the building.

The Central Park model contains a reference to a Cartesian point (LoGeoRef30). However, it is not clear which CRS is referenced. The remaining 4 models do not contain attributes according to LoGeoRef30. Concurrently, all models do not contain attributes concurring with LoGeoRef40, i.e. they do not contain other coordinate reference points. As expected attributes for LoGeoRef50 are missing in all models, since those attributes are incorporated in IFC 4, while all validated models are IFC 2x3.

In conclusion, none of the IFC-models contain sufficient attributes for georeferencing. Even though manually affining the IFC-models is not the optimal solution, the 5 IFC-models are placed on their approximate position by affining using a 3D Affiner in a FME workspace (Appendix B).

5.2 Visualisation

The results after validating and converting the IFC-models into the PostgreSQL database is a web-based viewer available on <http://broekhuizen.link/ces/3dlas.html>, or

<http://broekhuizen.link/ces/3dlasspace.html> which only shows the legal spaces without building elements. The 3D tiles are styled transparent, so that the user can see every room in a building. The viewer can select a spatial unit and see the concurring attributes (Figure 27). Next to the 3D parcels, building elements are shown for context to the building. An address can be found through the search bar.

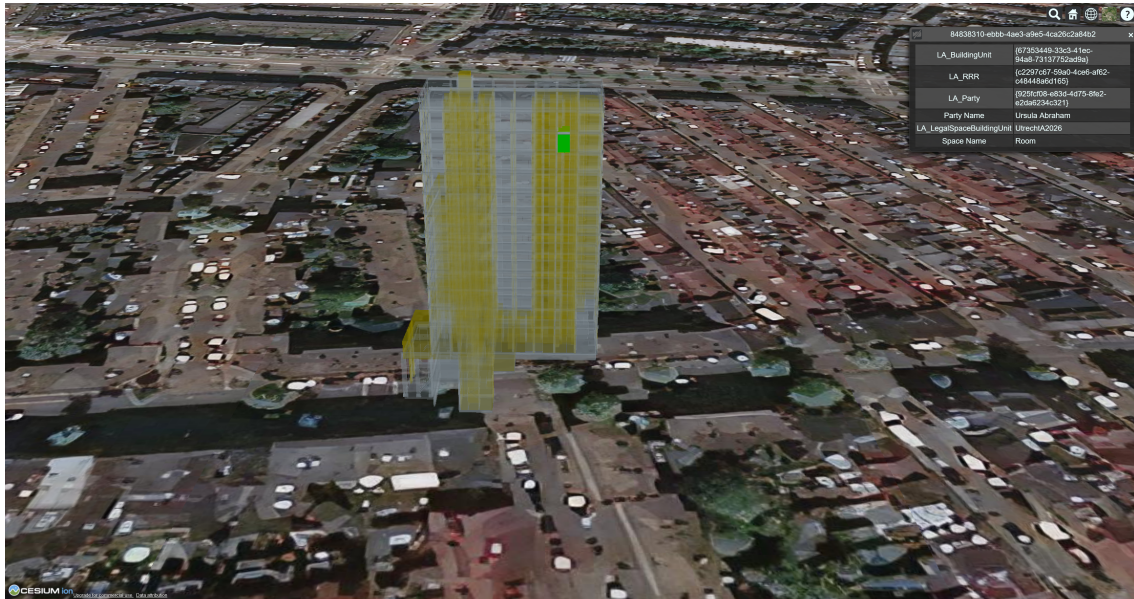


Figure 27: Cesium Viewer Showing the Conceptual 3D LAS

5.3 Feedback From Environment

User groups are asked to deliver feedback on the validation process and the conceptual 3D LAS. The architect replied, and acknowledged the lack of georeferencing. According to him, georeferencing is not common practice in his workfield. To apply georeferencing, a suitable method and more knowledge is needed. For the relation to the 3D LAS, for a designer the knowledge is present to add a propertyset. However a method needs to be known to who and how the contents can be filled, i.e. the indexnumber.

6 Discussion and Conclusions

This research focused on the challenges that are encountered when using real-world IFC-models for the registration of apartment rights in a 3D LAS, in this chapter first the research is reflected upon in the discussion subsection. Thereafter, answers to the research questions are given in the conclusion (6.2), and the recommendations and guidelines are presented. Possible future work is discussed in subsection 6.3.

6.1 Discussion

For this research 5 IFC-models were collected, validated and used as input for a prototype 3D LAS. To reflect on this research, some issues have to be taken into regard. The built 3D LAS prototype includes LADM components, however LADM is not fully integrated and only integrated in the DBMS. Furthermore the IFC-models used as input are mainly as designed IFC-models. In a 3D LAS the used IFC-models should be as-built, as this reflects the real-world situation. In the prototype 3D LAS only IfcSpace entities are modelled as legal units, as the Dutch law does not allow walls and other building elements to be included as legal units. However, with the technological developments, and further research into a 3D LAS, it should be reconsidered if building elements could be included as legal units. Concurrently, the conceptual 3D LAS DBMS does not preserve all IFC attributes. Incorporating all attributes into the DBMS complicates the DBMS. However in the file-based approach attributes are preserved. A solution should be applied to incorporate relevant attributes into a 3D LAS DBMS.

The workflow to validate and convert IFC-models are carried out using FME Desktop. Even though FME can handle a wide variety of file types, the IFC-reader is not optimal (i.e. hard to expose and relate all attributes), additionally the 3D analysis tools available in FME Desktop are brief. Therefore 3D analysis was done inside the PostgreSQL database. Additionally, FME Desktop is proprietary software. Even though additional software (FME Server) can be used to automate the workflow, in which users do not require a license for the software, for further development it has to be considered whether or not to use proprietary software or to choose or create an open source solution.

User groups were involved in the methodology, however the final report focuses more on the technical issues than the user groups. Since user groups are the end user of a 3D LAS, user groups can be more involved. Further research in this is recommended. Another reason to involve user groups is that they potentially can deliver input in the form of real-world BIM/IFC-files. Research has been carried out with fictional models. This research focused on real-world models. An added value of this is that it represents the final workflow of a 3D LAS better, as a LAS is dependant on the input of users, rather than creating models themselves. Therefore further research should continue on testing real-world IFC-models. However to establish this more real-world IFC-models should be collected, which is hindered now by the low availability of open IFC-models.

6.2 Conclusion

The research question is formulated as: *How should IFC-models be structured to effectively be reused as input for 3D LAS?* The accompanying research sub-questions are stated and answered, where after the main research question is answered. First, *Which technical, legal and organizational complications are encountered when using IFC-models as input for 3D LAS?* The technical, legal and organizational complications are explored and presented (3.4). Technical complications are tested for the 5 collected IFC-models. The second sub-question is formulated as: *Which solutions are recommended for those complications?* Possible solutions for technical complications are formulated in the recommendations and guidelines. To answer the third sub-question: *What are the different interests and benefits of user*

groups when using IFC-models as input for 3D LAS? two stakeholders were interviewed (3.5). Main concerns are the reuseability of IFC-models. As the architect noted that supplied IFC-models are not being maintained after the design, and the employee of the municipality noticed that collected IFC-models are not always structured the same, which makes it difficult to standardize its input in a digital twin. The last sub-question: *Which of the technical complications are encountered when testing real-life IFC-models as input for the Dutch LAS, and how can they be resolved?* Is answered by validating 5 real-world IFC-models and use these as input for a conceptual 3D LAS. For the complications that arose, possible solutions are stated, and formulated in the recommendations and guidelines.

6.2.1 Recommendations and Guidelines

Based on the results of the validation process, recommendations and guidelines are formulated. They provide recommendations and guidelines on how to effectively structure IFC-models to be reused as input for a 3D LAS.

- To extract legal spaces, rooms have to be included in the IFC-model as IfcSpace
- IfcSpace should contain a propertyset which include the apartment index number, cadastral parcel number, complex number, space type and municipality, to link the legal spaces to the Dutch LAS.
- Concurrently IfcSpace can be grouped, but these groups should not be included as a (duplicate) IfcSpace volume.
- Attributes for georeferencing should be included in the IFC-model. It is recommended that IFC4 files with attributes for georeferencing are preferred above the IFC2x3 files. For existing IFC 2x3 models it is necessary to enrich the IFC files with attributes complying to LoGeoRef30 and/or LeGeoRef40.

The recommendations and guidelines are formulated based on the findings in this research on the reusability of IFC-models as input for 3D LAS. Its focus was on the technical challenges that arose. Hence 5 collected real-world IFC-models were validated on the existence of IfcSpace, its relation to the LAS, valid geometries, spatial relations, and georeferencing. 2 out of 5 models contained IfcSpace. For creating spatial units in a LADM 3D LAS the existence of IfcSpace is essential. Even though the spaces can be added automatically with software such as Revit, this does not result in a complete and accurate representation of all spatial units. Therefore it is recommended that for the reusability for a 3D LAS IfcSpace should be added by the designer of the IFC-model.

Concurrently, the IFC-models did not store information which could link them to the Dutch LAS. It is advised that a propertyset is included in the IFC-model which represent the apartment index number, cadastral parcel number, complex number, space type and municipality.

Another validation carried out was checking for overlap. Only one IFC-model contained overlap. To resolve this overlap the designer should alter the IFC-model, this can be done by using the validation method used, and using the result to alter the spaces where overlaps occur, until there is no more overlap. Additionally, when grouping spaces IfcZone can be used. It should be noted that although the IFC-models were added to the prototype 3D LAS, in a real 3D LAS overlap should not be valid input, as it does not fulfil the legal requirement of spaces being mutually exclusive.

Georeferencing proved to be difficult for the IFC-models. This is known issue for IFC 2x3 files. The IFC4 files are designed to be better able to georeference. However no IFC4 files were collected, hence this should be further researched. IFC 2x3 files can be manually placed on the approximate position, however this is a time-consuming process, and the result is an approximate rather than exact position.

In the context of a 3D LAS approximate positions can not be accepted. Hence it is recommended that IFC4 files with filled in attributes for georeferencing are required above the IFC2x3 files. For existing IFC 2x3 models it is necessary to enrich the IFC-file with the correct reference coordinates and truenorth.

It should be noted that although these recommendations and guidelines present guidelines for technical challenges, these recommendations and guidelines are related to legal and organizational challenges. Mandate is needed to enforce standards, and a change in workflow for designers to check for these technical issues is needed. In this process, the variety of user groups and their interests have to be taken into account.

6.3 Future Work

Proposed future work for using IFC-models as input for 3D LAS include:

- Research on legal and organizational challenges. The focus of this research was on the technical challenges that arise when using IFC-models as input for 3D LAS. However to implement the given recommendations and guidelines legal and organizational challenges should be addressed. A legal mandate, combined with standards, have the possibility to direct user groups when designing and exchanging IFC-models.
- A larger dataset of, and more variety in IFC-models. For this research 5 IFC-models were collected. A larger dataset of more IFC-models, with a wider variety in designers, would give a better insight in the ability of real-world IFC-models as input for 3D LAS. The availability of open IFC-models however is low, it should be assessed which incentives can be used for designers to share their IFC-models for research. Concurrently IFC-models of other countries could also be tested against the used validations.
- Research on using IFC4 IFC-models. All collected models for this thesis are IFC 2x3, which have known issues with georeferencing. For the validation FME Desktop and PostgreSQL were used. Spatial relations are defined by executing an intersection function. A DE-9IM matrix could give better insight in spatial relations, and also define the type of relation. It should be further assessed which software tools allow for this analysis. In addition, for 3D LAS boundaries, and the direction of boundaries are important. Future research could focus on the validation of topology and boundaries.
- Elaborate on the validation of spatial relations. In this thesis, the validation of spatial relations focused on identifying overlap between legal spaces. However, this could be elaborated upon by also validating all building elements. Concurrently a method should be developed to identify gaps in IFC models. A method which defines spatial relations between 3D geometries in the form of i.e. a DE-9IM can provide more insight in the spatial relations, however this was not available for 3D geometries in the used software.
- Automation of the workflow. The workflow presented in this thesis consists of a series of steps, which can be carried out with FME Desktop. However there are options to automate this workflow with i.e. FME server. This will have the advantage that user do not need to install proprietary software, and additionally that automations can be built in, such as a subsequent run of workspaces, and an automatic update to the 3D tiles when the database is uploaded. This option could be further developed.
- Research on the visualisation of a 3D LAS DBMS. The developed 3D LAS in this thesis contains a PostgreSQL database, which is visualised by converting its contents to 3D tiles. However, no

direct translation between the database to the visualisation is made. A conversion is still needed to visualise the contents of the database, hence the visualisation does not directly show changes made in the database. Even though there is Open Source software to directly represent contents of a database (i.e. GeoServer), this was not fit to represent the 3D geometries of the conceptual 3D LAS database. Future work can investigate the possibilities to directly view the contents of the database in an online viewer.

- Elaborate integration of the LADM. The LADM is applied to the conceptual 3D LAS in this thesis, however firstly it is applied in a simplified form. In a real 3D LAS the LADM should be applied containing additional classes. Secondly the parties and rights are all fictional. This is because ownership information was not available in and for the IFC-models. The integration of ownership information inside BIM. IFC-models should be further investigated and standardised for a Dutch 3D LAS.
- Research with real-world IFC-models and real-world RRR's, parties, and indexnumbers. Since grouping of legal spaces and the real RRR's and parties of the IFC-model are unknown for the collected IFC-models in this thesis, and not implied in the IFC-models, fictive parties, RRR's, and indexnumbers are created. Overall this represents an incomplete, simplified example of the LADM. Future work can focus on IFC-models where the parties, RRR's and indexnumbers are known, to assess challenges that arise when using this real-world data for a 3D LAS.

Appendices

All workspaces and custom transformers are available on github: <https://github.com/superjumpyllion/IFCAsinputfor3DLAS>

Appendix A

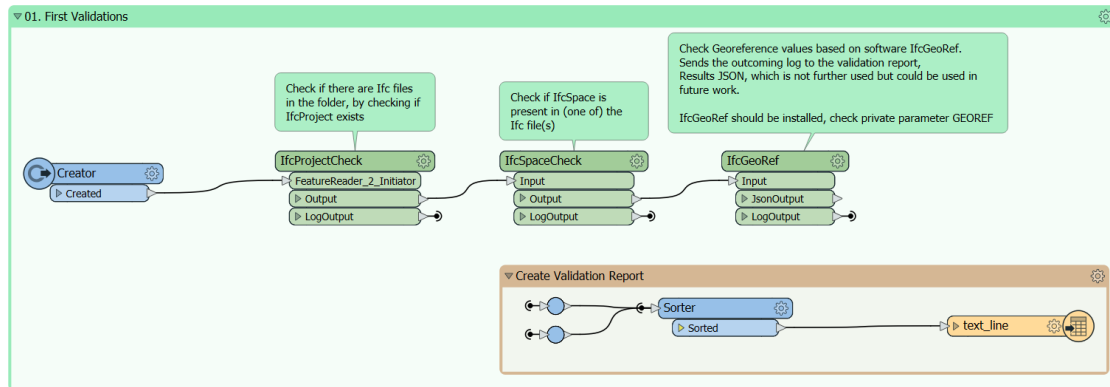


Figure 28: Workspace: 1_IFCspaceAndGeoRefCheck - Validates if IfcSpace is present and generates a IfcGeoRef report containing information about georeferencing capabilities

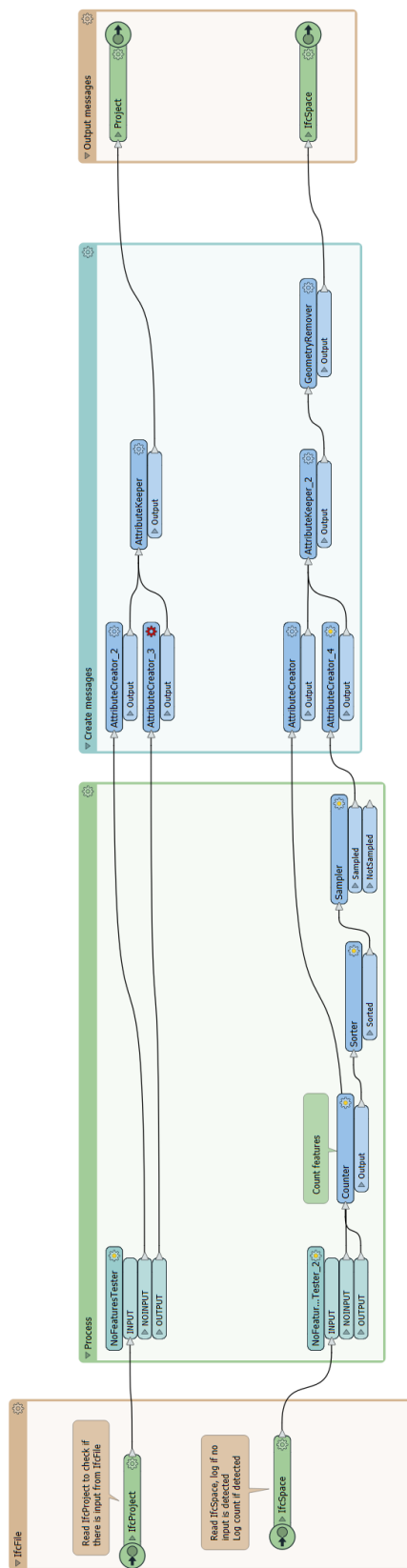


Figure 29: Custom Transformer: IfcSpaceCheck

Appendix B

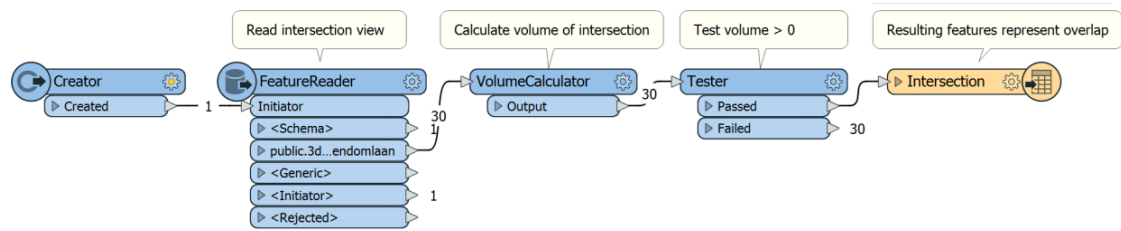


Figure 30: Workspace: 3.Intersection - Reads the 3D intersection view from the DBMS, calculates volumes and results volumes 0 as overlap.

Appendix C

Appendix D

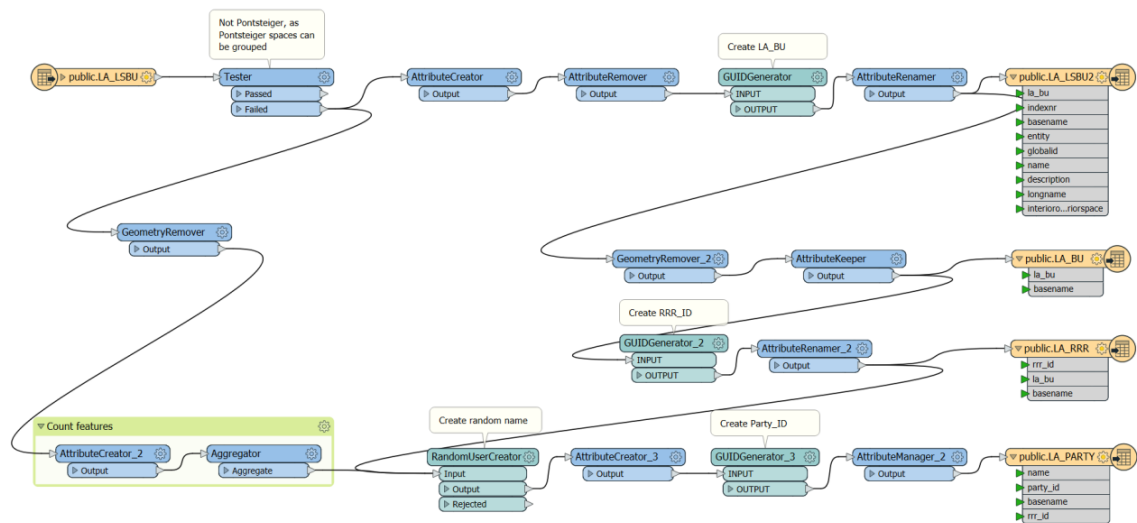


Figure 32: Workspace: 4-FictiveLADMa - Reads LA.LegalSpaceBuildingUnits and generate fictive parties and relations

Appendix E

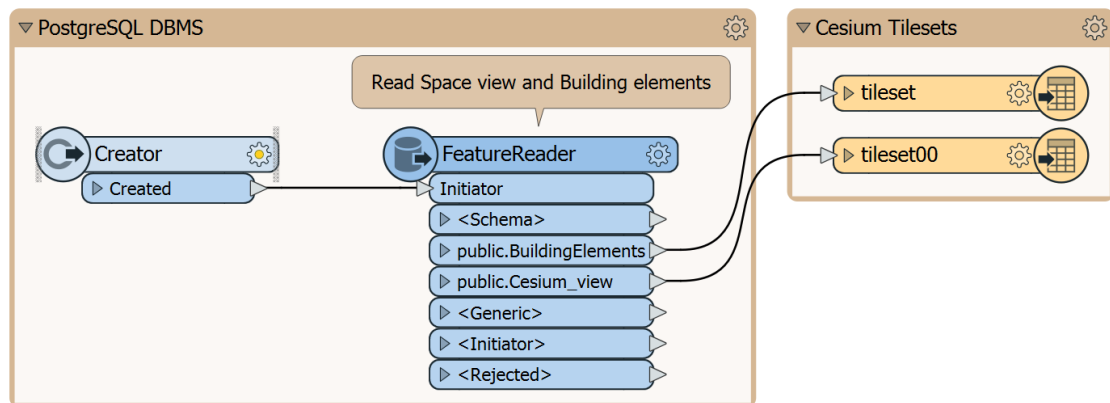


Figure 33: Workspace: 5_DBMStoCesiumtiles - Read Cesium_View from DBMS and write to Cesium Tiles

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