GIMA
Geographical Information Management and Applications

Working with Open BIM Standards to Source Legal Spaces for a 3D Cadastre

GIMA MSc. Thesis

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Version (Final) – 07 March 2017

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Keywords: BIM, IDM, BPMN, MVD, *Omgevingswet*, LADM, IFC, 3D Cadastre

Abstract

Much work has already been done on how a 3D Cadastre should best be developed. An inclusive information model, the Land Administration Model (LADM ISO 19152) has been developed to provide an international framework for how this can best be done. While this generous framework encompasses a wide range of eventualities, it does not prescribe the data format. One existing source from which data could be obtained is 3D Building Information Models (BIMs), or more specifically in this context, BuildingSMART's Industry Foundation Class (IFC).

Obtaining data is only one part of the process from moving from a 2D to a 3D Cadastre. A workflow, preferably digital, also needs to be determined to support this. This digital workflow would determine what the 3D Cadastre needs from a 3D IFC BIM and the process of extracting it in addition to exchange requirements. Foundations, however, would need to be laid in order to facilitate this process.

To begin with, the fact that the Industry Foundation Class (IFC) has more than 800 entities means that there is more than one way to satisfy the requirements of cadastral legal spaces. In addition to being large, it leaves options open for adapting the model without entering into the lengthy process of changing it. Working from what is already there would enable data for a 3D Cadastre to be extracted at all stages of the BIM lifecycle, from initial design to the end of the life of the building.

Secondly, experience has shown that process harmonization between organizations is very complex and can lead to conflict. In addition, the processes which need to be harmonised differ from country to country. If possible, therefore, it is something wiser to avoid. This means that while a workflow detailed in BuildingSMART's Information Delivery Manual (IDM) may be useful within the complex collaborative environment of a BIM project, it is not something which would be standardised within the international Land Administration community. Having said that, communicating the extraction process to the building world in their own *lingua franca* could be beneficial.

Acknowledgements

Peter van Oosterom for his assiduous attention to detail and for his interest in the project. Wilko Quak for his practical help and for getting me over the finish line. Jakob Beetz for his expert knowledge of BIM open standards and how they compare with GIS and being prepared to be involved for the 'intellectual curiosity'. Jeroen van der Veen for giving this project a business context and for his insights into how the real world works.

My husband and children for their support. And for my Mum - who always thought GIS was a great idea.

List of Acronyms and Dutch Terms

BIM Building Information Model (see Figure 13)

IDM Information Delivery Manual

IFC Industry Foundation Classes

BPMN Business Process Modelling Notation

LADM Land Administration Model

Omgevingswet Environs Act

Kadaster the Dutch Land Registry Office and Large Scale Topographic Map combined in one organisation

3D Cadastre a 3D Land Registry

HVAC Heating Ventilation and Air Conditioning

2D 2 Dimensional

3D 3 Dimensional

City GML City Geographic Mark-up Language. An exchange format used to exchange data between 3D models.

OGC Open Geospatial Consortium An international voluntary consensus standards organization responsible for making quality open standards for the global geospatial community.

LandXML is a non-proprietary XML (eXtensible Mark-up Language) data file format containing civil engineering and survey measurement data commonly used in the Land Development and Transportation Industries

InfraGML A mark up language currently in development by the OGC which will leverages off from LandXML and which will be compatible with the IFC

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1 Introduction and Problem Definition

This chapter sets the scene for the topic under investigation. It puts the topic in context on a national scale, but always with reference to what is happening worldwide. It begins by looking at the service the Dutch *Kadaster* currently provides, with translations and explanations of key terms. It then discusses how society would benefit from the proposed solution, which would make the Dutch *Kadaster* more cost effective and efficient. This is done with reference to the moves already afoot to add 3D information to the cadastral database, for example the Delft Station case study.

How a society would benefit from a 3D cadastre could be described as the front end of the problem, while how this would be achieved is the back end. As described in Chapter 1.3 this 'back end' is what interests the scientific community. That the scientific community were interested in the work was illustrated by the fact that the paper was accepted for presentation at an international conference.

We, the authors, firmly believe that the topic is of interest to many different parties including academic colleagues, government officials and industry representatives. For academic colleagues as it involves topics at the forefront of current research, for government officials as it can make the services they provide more cost effective and efficient and for industry representatives as where there are changes to infrastructure, there are business opportunities. Exactly what and how is discussed in Chapters 1.5, 1.6 and 1.7.

1.1. Brief Background

In the face of the push towards 3D and the smart society, the traditionally separate worlds of Building Information Models and Geo Information are coming together. This point was recently made by Bart De Lathouwer, head of the Open Geospatial Consortium (OGC) (Lathouwer 2016) but is also underpinned by what is happening in the Netherlands. For example, the Dutch data dictionary, the Concepten Bibliotheek Nederland, (CB-NL) connects up terms from the world of Geo Information and Building Information in one taxonomy (Reuvers 2016).

The use, not just of 3D but of integrated geo- and building information, is being embraced by a number of institutions within the Netherlands. These include the *Rijkswaterstaat* (Veldhuis 2016) - the national organization which builds and maintains infrastructure - and the Municipalities of Rotterdam (Goos 2016) and Amsterdam (de Maa 2016). Within the Dutch *Kadaster* itself, the department which administers the *Basisregistratie Grootschalige* Topografie (BGT) - a highly-detailed large-scale digital map of the Netherlands - is also moving toward 3D based on building information (BIM). This is being done within the framework of the *Omgevingswet* (Environs Law). The part of the *Kadaster* which works with legal spaces, however, remains based on 2D. This part of the *Kadaster* administers Ownership Information (*Kadastraal bericht eigendom*) and the Map of Legal Spaces (*Kadastrale Kaart*) (Table 1 and Figure 1) as well. It is the written Ownership Information document (see Table 2 and Figure 2) which contains the legally-binding definition of space in the form of the size of the spatial unit (grootte), for example 220 m2.

Explanation of the Dutch Kadaster's Map of Legal Spaces		
	Explanation in Dutch	Explanation in English
1	Kadastrale gemeente Sectie Perceel	the municipality the spatial unit is registered in (Ambt-Doetinchem) and its unique number (711) and section (P)
2	Perceelnummer	Unique number repeated (711)
	Huisnummer	House number in red (25)
3	Vastgestelde kadastrale grens	Spatial unit boundary which has been measured by the *Kadaster* and is thus 'fixed' (Henssen 1996).
4	Voorlopige kadastrale grens	Spatial unit boundary which has been drawn on the map by an intermediary and which still needs to be measured and 'fixed'.
5	Administratieve kadastrale grens	Spatial unit boundary which has been drawn on the map by the *Kadaster* but which still needs to be measured.
	Bebouwing	Buildings themselves (outlined in red and with red house numbers).
	Overige topografie	Other topographical features (outlined with a narrower black line than the fixed boundaries (3)).

Table 1 Explanation of the Dutch Kadaster's Map of Legal Spaces

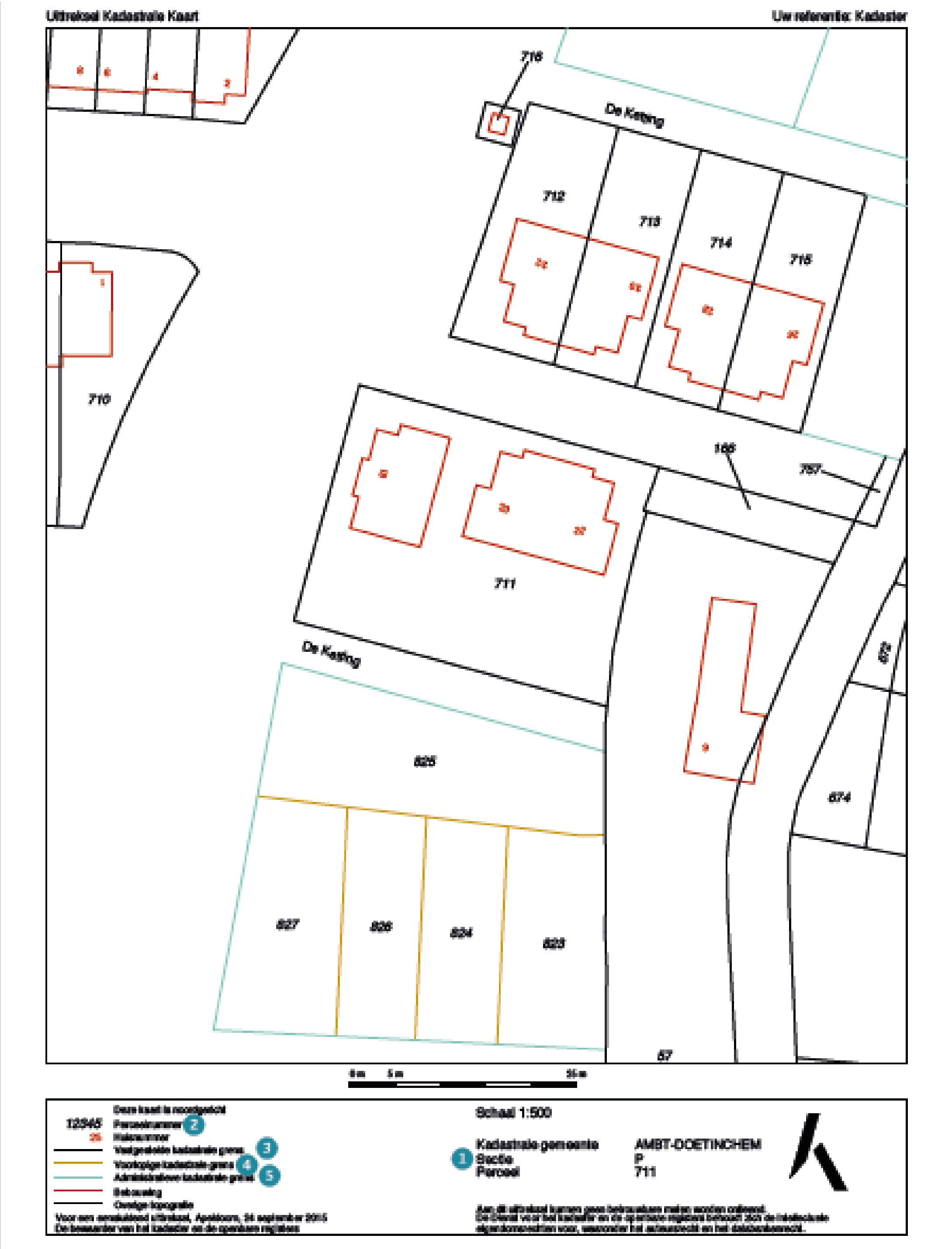
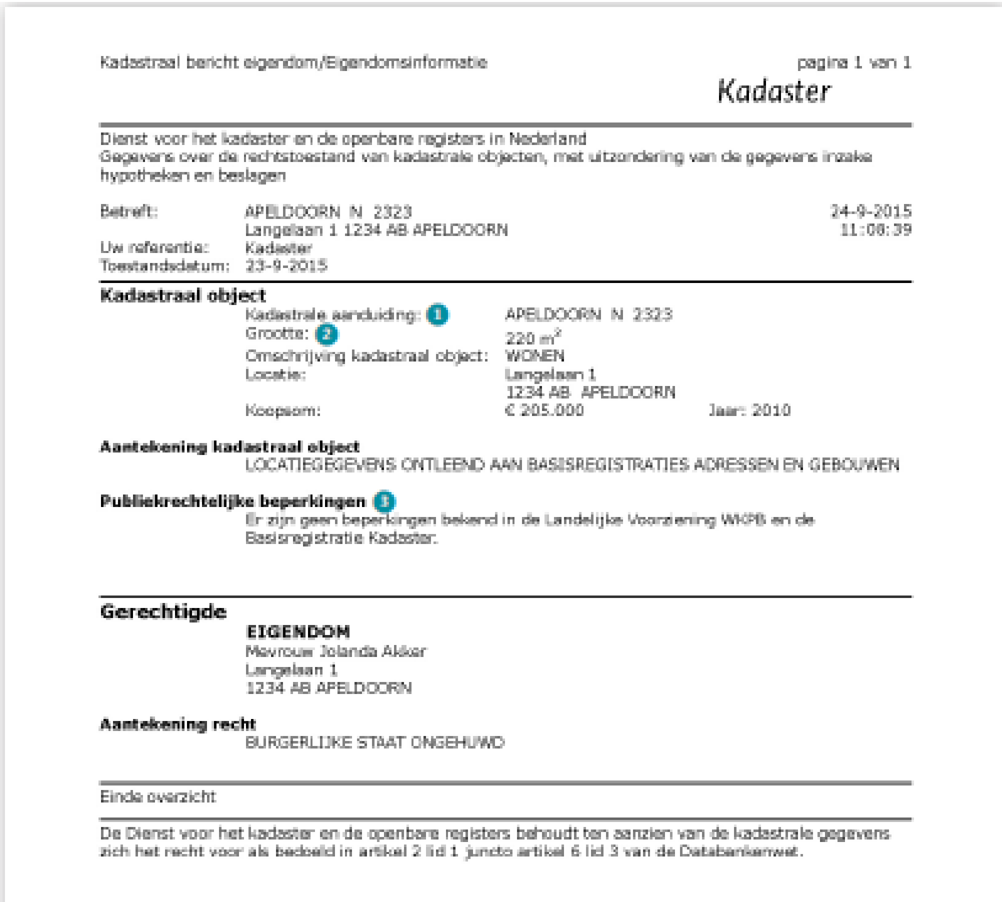


Figure 1Map of Legal Spaces www.Kadaster.nl

Explanation of the key features of the Ownership Information document		
Number	Explanation in Dutch	Explanation in English
1	Kadastrale aanduiding (uniek nummer van dit perceel)	Land Registry/Cadastral designation. (Unique number of the spatial unit)
2	Grootte (oppervlakte van het perceel)	Size (currently legally-binding definition of space in the Netherlands)
3	Door de overheid opgelegde beperkingen.	Restrictions imposed by the government which determine what can be done with the spatial unit. For example a. Listed building b. Situated within a nature reserve or national park c. Soil protection (owner is required by law to register polluted soil)
	Met uitzondering van de gegevens inzake hypotheken en beslagen	Without details concerning mortgages and possessions
	Omschrijving kadastraal object: WONEN	Land use – in this case ‘domestic housing’

Table 2 Explanation of the key features of the Ownership Information document



Kadastraal bericht eigendom/Eigendomsinformatie

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Kadaster

Dienst voor het kadaster en de openbare registers in Nederland
Gegevens over de rechtstoestand van kadastrale objecten, met uitzondering van de gegevens inzake hypotheken en beslagen

Betreft: APELDOORN N 2323 — 24-9-2015
Langelaan 1 1234 AB APELDOORN — 11:08:39
Uw referentie: Kadaster
Toestandsdatum: 23-9-2015

Kadastraal object

Kadastrale aanduiding: 1 APELDOORN N 2323
Grootte: 2 220 m²
Omschrijving kadastraal object: WONEN
Locatie: Langelaan 1
1234 AB APELDOORN
Koopsom: € 205.000 Jaar: 2010

Aantekening kadastraal object
LOCATIEGEGEVENS ONTLEEND AAN BASISREGISTRATIES ADRESSEN EN GEBOUWEN

Publiekrechtelijke beperkingen 3
Er zijn geen beperkingen bekend in de Landelijke Voorziening WKPB en de Basisregistratie Kadaster.

Gerechtigde
EIGENDOM
Mevrouw Jolanda Akker
Langelaan 1
1234 AB APELDOORN

Aantekening recht
BURGERLIJKE STAAT ONGEHUWD

Einde overzicht

De Dienst voor het kadaster en de openbare registers behoudt ten aanzien van de kadastrale gegevens zich het recht voor als bedoeld in artikel 2 lid 1 juncto artikel 6 lid 3 van de Databankenwet.

Figure 2 Ownership Information with legally-binding space definition (www.Kadaster.nl)

1.2. Relevance for society

As was discussed in the background chapter, the department of the Dutch *Kadaster* which administers legal spaces is not yet in 3D, although there are moves within the organisation itself to become so. Becoming 3D would not only make the *Kadaster* more efficient and cost effective but would also reduce the number of legal disputes over property. An example of this is that of 'inkijk' or 'overlook. Dutch law stipulates that two metres should be left between windows which allow one property owner to look into the window of another property owner. Figure 3 illustrates a situation where one of the balconies in a row of houses has been fitted with a window which looks directly into the window of another owner. The 3D illustration clearly shows that this should never have been allowed. Although the previous owner may have verbally agreed to it, without legal documentation the current owner could easily dispute this although this would have had to have been done within a twenty year time frame. Figure 4 illustrates a number of far more difficult problems to solve. This complex streetscape includes a road elevated above an area for parking bicycles and buildings which protrude over the spatial units of others.

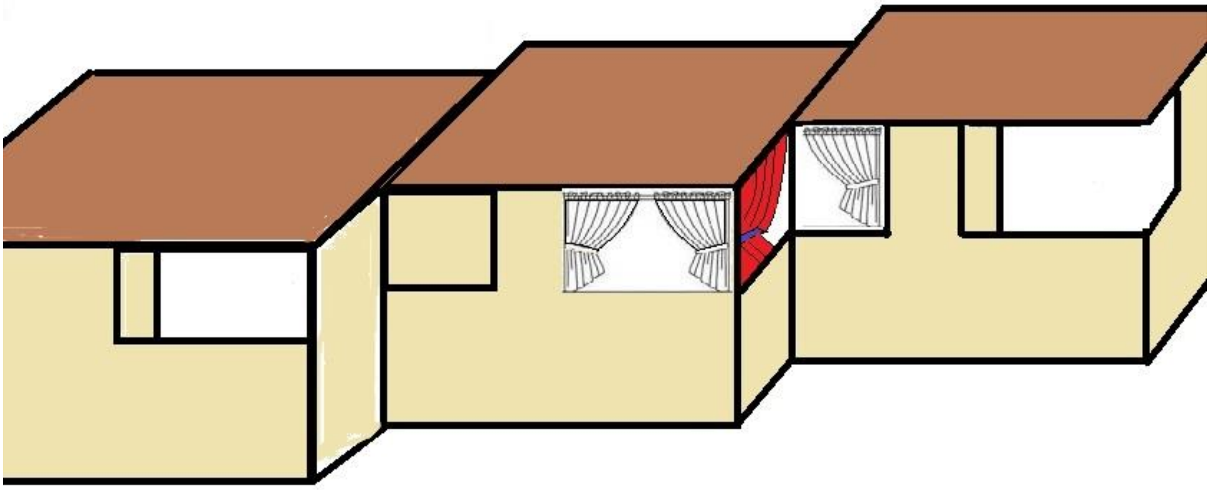


Figure 3 A latterly placed window (with red curtains) which infringes on the rights of the middle-house's legal space with regards to 'overlook' – it now looks directly into the other property's window and is well within the 2 metres distance stipulated by Dutch law. It was formerly an open balcony

Figure 4 Image from the centre of Amsterdam (World Trade Center) showing a complex and difficult- to-register streetscape

A point key to this discussion is that while the current system legally encompasses the idea that the owner of a property is the owner of the space above it and that below it – its height and depth- it neither visualises nor fixes these boundaries. Put simply, while the Map of Legal Spaces (*Kadastrale Kaart)* works in reality with 3D spaces, it visualises and fixes them in 2D. It would be beneficial to all involved if the reality matched how it was recorded in the system.

Unfortunately, in spite of the fact that it would provide many benefits there would be high costs, not only with regards to setting the system but maintaining it (Lathouwer 2016). The data would need to be procured and then entered into the database. It would then need to be updated whenever any changes occurred to the property. An example of such a change is if a house extended, or if the soil of a property is reported as being polluted.

One interim step which has recently occurred and which was reported in the Dutch newspaper the *Volkskrant* (Weijer 2016) has been the submission of 3D visualisations to the *Kadaster*. This 3D information has been made accessible via a (direct) link to the cadastral map. (Stoter *et al* 2012) These visualisations are of the newly-completed station in Delft. The station which included offices, the station itself and a tunnel, has multiple owners (NS Vastgoed, Railinfratrust, Gemeente Delft) as illustrated by the different colours in Figure 5.

This 3D interactive pdf was, however, not part of a 3D topological map of legal spaces but an addition to the current 2D registration. Its ground-breaking registration took two years to be finalised (de Riet 2016) due to the fact that the registration was initially completed in 2D and then reworked to include 3D information (Stoter et al 2016). If the initial registration had been accompanied from the beginning by a 3D legal space, it would have been completed in a matter of weeks rather than years (de Riet 2016). Clearly, requiring that the registration be begun in 3D rather than 2D would be a more efficient workflow.

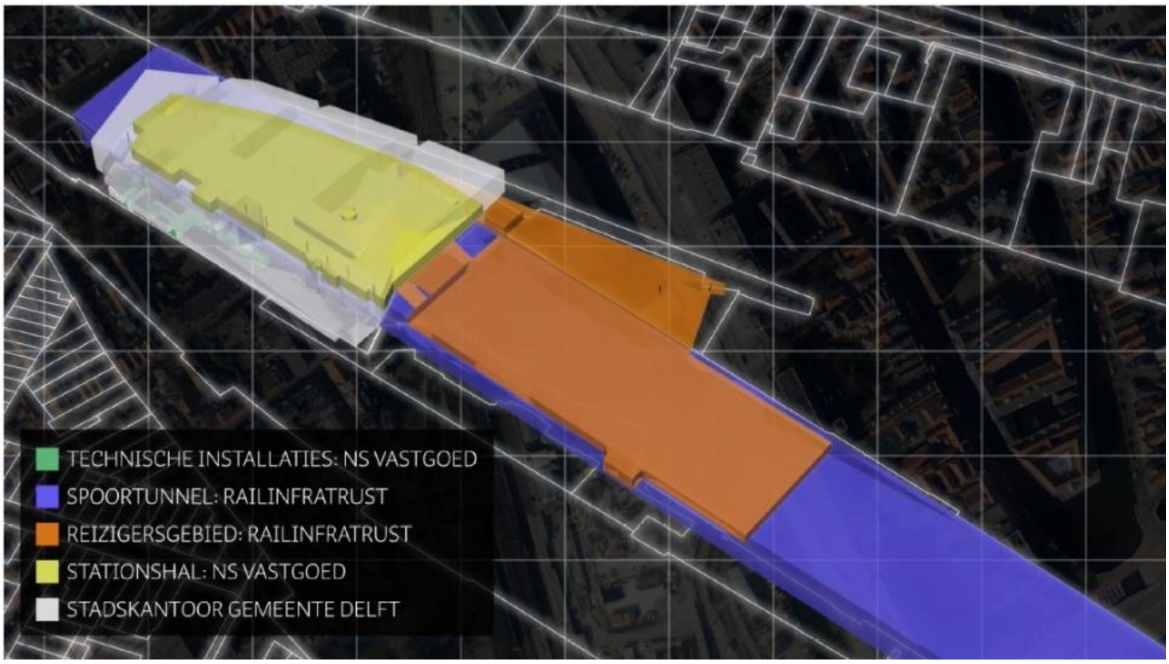


Figure 5 3D Visualisation of Delft Station showing multiple ownership

The inclusion of 3D visualisations in the land registry system is a great step forward. Ideally, however, a 3D Cadastre would involve more than visualisations and registration would begin in 3D rather than 2D. Interactive, topological models stored in a spatial database would allow queries to be performed, data to be validated automatically and interactive visualisation (Stoter *et al* 2016). Additionally, if a 3D registration were required, it would be better to begin with a 3D volume. This case will be discussed in more detail later in this report.

To sum up this section, Dutch citizens would benefit from having a 3D Cadastre. Although there would be set-up and maintenance costs, the further automation of this service would save money on processing and legal fees in the long run. For example, no longer would multiple documents need to be studied in order to come up with answers concerning a property. Instead a database could be queried to provide a correct answer such as whether it is a listed building. Rather than paying lawyers to determine who is responsible for repairing and maintaining a communal elevator, this could have been decided at the beginning and clearly demarcated using a different colour on a 3D model.

1.3. Relevance for Science

While the relevance of this topic for society could be described as the front- end of a 3D Cadastre; its relevance for science concerns the back-end. The front end would be the web service connecting to the data base and providing answer to queries put to it by consumers. Whether your property has restrictions imposed on it because it is situated in a nature reserve could be easily established by typing in a question. The back-end, however, is a more complex proposition. It involves questions including how such a system can best be built, and how the data necessary for it best be collected, integrated and maintained.

The research conducted for this project attempted to answer these questions in two ways. Firstly, it looked at whether data from BIM models could be re used as for integration into a 3D Cadastre. Secondly, a workflow modelled in BuildingSMART's Business Process Modelling Notation, part of the Information Delivery Manual was designed. The workflow modelled the process of obtaining the data.

There was much real interest worldwide from the academic community on this topic. When the paper proposal was submitted to the 5th International FIG Workshop on 3D Cadastres (FIG = International Federation of Surveyors) it was labelled 'An fascinating topic' and awarded two 'strong accept's by the reviewers. The integration of open standards into government systems and research into ways to make them interoperable with each other forms part of research being done not only here in the Netherlands but abroad as well. For example, with regards to the re use of data from BIM models, the research ran parallel with a project in Australia (Atazedah *et al* 2016).

1.4. Why I chose this topic

Having been lucky enough to have attended the conferences organised by Jantien Stoter to stimulate the evolution of City GML in the Netherlands and to have translated the toolkit for its use for Geonovum and then to have translated the top 2000 terms of the CB-NL meant that a thesis topic involving the integration of standards was of particular interest to me. Wanting to know more about spatial databases meant that Delft was the place to look for supervision. I had already found a co-supervisor in the form of Jakob Beetz, a BIM expert from the Technical University in Eindhoven which married happily with the fact that Professor Peter van Oosterom and Wilko Quak were looking for someone to explore the use of data extracted from Building Information models in the context of a 3D Land Registry System. While attending a further conference (Doorbraak 3D Inspiratiesessie Geo/BIM en 3D water), I met Jeroen van der Veen, the project manager responsible for organising the Environs Law's (Omgevingswet) Information House: Buildings. I asked him to join our project and he agreed with interest.

1.5. Who Should Read My Report and Why - Academic Colleagues

As mentioned above, a paper proposal based on my thesis was submitted to the 5th International FIG Workshop on 3D Cadastres (FIG = International Federation of Surveyors). In October, I travelled to Athens and presented my paper at this conference. In addition to the many interesting discussions with surveyors from all over the world about my paper, it was also peer reviewed. The comments and assessment (I received an average mark of 8.6) are affirmation that academic colleagues could well be interested in reading my report.

The reason why it is interesting is that it taps into research already being conducted throughout the world as well as complementing and extending it. The research in Australia (Atazedah *et al* 2016), for example, looked at the use of space objects for the representation of legal spaces but had not yet looked at them in the context of the IFC. Furthermore, the fact that BIM standards also model processes was something new. To top it all off, the workflow illustrated how the Netherlands is planning to obtain BIM information in an innovative, new way.

1.6. Who Should Read My Report and Why - Government Officials

One of the supervisors of my thesis is Jeroen van der Veen who works for both the *Kadaster* and the Ministry of Infrastructure and Environment (*Ministerie van Infrastructuur en Milieu - I&M*) He is the project manager responsible for the creation of the Information House: Buildings, a product of the department within the *Kadaster* which currently administers the *Basisregistratie Grootschalige Topografie* (BGT). He would like to include legal spaces in the dossier of each building registration to be submitted to the Information House: Buildings. He is particularly interested in examples of how this can be done in order to illustrate the usefulness of such a procedure to others.

1.7. Who Should Read My Report and Why - Industry Representatives

New developments to government information infrastructure systems can result in new work for industry. This may be direct assignments as industry subcontracts to government or indirectly through the purchase of commercial software adapted to the new development. For instance, the report about the Information House: Buildings (Pijpker *et al* 2015) states that building registrations which do not already include a digital BIM will need to have one made. It then says that this work will be subcontracted to industry.

If legal spaces are included in the Information House: Buildings registration dossiers, then this may also require work to be done retrospectively. Thus subcontractors would include these spaces in the BIM file. Additionally, software providers, such as Bentley who makes Autodesk, may develop functionality within their software to assist these spaces to be made. This could result in additional sales of their software.

2. The Organisation of the Research Project

2.1. Research Goals and Objectives

Goals	Objectives
Analyse the BIM/IFC information model and the LADM and find links	• Create a sequence or activity diagram of the best workflow • Make it with reference to the Land Administration Domain Model ISO 19152 • Implement a prototype in a database
Develop a conversion function which uses data from BIMs to construct 3D spatial units.	• Source data for use cases from a variety of properties best administered by a 3D cadaster to be used in the conversion function • Write a script to automate the process • Assess the converted/derived data (missing data, problems with conversion, data quality: volumes closed, no overlapping parcels) • Repeat and improve this process

Table 3 Research Goals and Objectives

2.2. Research Questions

These research questions are based on the goals and objectives above.

Main research question:

Can open BIM standards and IFC data be used as input for 3D Cadastral Registration?

1) *Based on research already completed in this area, what is the best way to conceptually map BIM data and ISO 19152 together in order to produce input suitable for the creation 3D Spatial Units?*

    a) *How do BIM, ISO 19152 and the requirements for a LADM- based 3D Cadastral model compare?*
    b) *How can BIM best be structured in order for it to be inoperable input for the 3D spatial input?*

2) *Which use cases of combined BIM and Cadastral data optimally illustrate the challenges which twenty-first century Smart Cities will throw at a 3D Cadastre?*

    a) *What types of object registration occur at a Cadastre?*
    b) *Which properties can be more adequately registered by a 3D Cadastre?*
    c) *How can these 3D cadastral entities be obtained from BIM and then incorporated into the design of conversion/derivation function?*

3) *What are the requirements for a conversion/derivation function from BIM to a Cadastral entity?*

   a) *What are the advantages and disadvantages of similar functions or function components (for example validation code) already in existence?*
   b) *How can they be incorporated into a new conversion/validation function?*
   c) *How do BIM Model objects and Cadastral Model objects compare?*
   d) *What points or features should be converted and/or derived?*

4) *How should a test or Database prototype and test conversion of the proposed solution best be generated?*

5) *How can the first conversion/derivation function be improved?*
   a) *What are the criteria for assessing the conversion /derivation?*
   b) *What are the guidelines for improving the conversion/derivation function?*

6) *How successful is the improved version of the conversion/derivation function?*

2.3. Out of Scope

A repository on a webserver serving as an example showcase for a potential user interface to the platform

LADM packages beyond the spatial unit package – thus administrative details and versioning for example

A GIS database – the files – although packaged for a GIS database - remain in IFC format

2.4. Who, When and Where

The research is a thesis which will complete a Master of Science in Geographical Information Management Applications. The candidate is Jennifer Oldfield and the supervisors are Jakob Beetz (TU Eindhoven), Jeroen van der Veen (Kadaster and Ministry of Infrastructure and Environment) and Wilko Quak (TU Delft). The professor is Peter van Oosterom. The project was carried out in‘s-Hertogenbosch at the students home during the period November 2015 to December 2016 and officially began when this proposal was accepted. Research continued while the candidate was in Melbourne, Australia from late April to early May 2016. A mid-term presentation took place in June 2016 in Delft and a final presentation in March 2017 in Utrecht. A number of meetings with both the professor and supervisors took place during that time, in addition to the written feedback. For more details, see the Time Schedule below.

2.5. Methodology

The methodology consists of four main phases between initiation and close out - analysis, design, implementation and evaluation.

1. Analyse other information models and exchange formats (BIM LADM) already in use.
   Analyse how data has been derived/extracted from them in the past (BIM/IFC to CityGML).
   Analyse other ETL scripts/software and study relevant conversion and validation functions.

Analyse different types of 3D Cadastral registration situations and select a number of use cases.
Document these cases, finding relevant data (including design/BIM data), and involved RRRs and Parties 3D Cadastral requirements

2. Design the sequence or activity diagram which maps BIM to 3D spatial units.
   Design a data base schema based on this
   Design a conversion function which also validates based on this sequence or activity diagram
3. Implement the mapped data and the conversion and validation function in a prototype environment
4. Evaluation. Test the information model and the conversion and validation function
   Assess how successful the above approach is according to the following criteria and decide how the first conversion/derivation function can best be improved.
   Provide guidelines to prepare design/BIM data better suitable for deriving 3D volumetric parcel)
   Enrich/restructure some sample design/BIM data
   Convert again and assess if work flow starting with enriched design/BIM data is indeed an improvement (quality, efforts: automated/manual)

2.6. Material

Material used includes literature detailing where other countries in the world are up to with regards to this topic, a Compaq laptop and some software –Microsoft Office, Microsoft Visio, IfcDoc to design the information model in, Solibri Model Viewer to view the use cases and Autodesk and Archicad run on a Virtual Machine. IfcOpenShell and PythonOCC were used to explore the option of programming with the IFC.

Material	Details
Literature	See references
Hardware	HP Compaq laptop AMD E-300 APU with Radeon™ Processor 1.30 GHz Microsoft 8.1 Enterprise
Data	Selected Use Cases • 3D BIM data • Cadastral Data (Maps detailing parcels; rights – the 3RRR's; persons and or owners)
Software	Microsoft Office 2013 Microsoft Visio 2013 Autodesk on a Virtual Machine Archicad on a Virtual Machine Solibri Model Viewer IfcDoc IfcOpenShell PythonOCC

Table 4 Research Materials

2.7. Data for the Use Case

The data required should be 3D BIM data and Cadastral data for the use cases. This should be BIM data which showcases the vertical development (Rajabifard 2015) and other challenges which a twenty-first century 3D Cadastre will be required to face.

The following dataset was used in this report. It was obtained from the website of the Duraark project (www.duraark.eu) and was put there by the United Kingdom's National Building Specification in IFC format.

I tried to source other relevant data at a conference (BIM Loket COINS day) and in Australia, but to no avail.

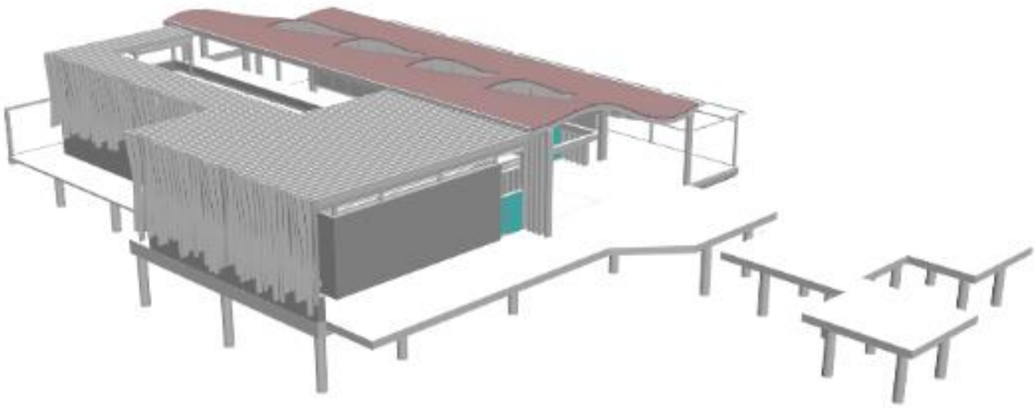


Figure 6 Usecase 1: Lakeside Restaurant

In the end, while I succeeded in finding IFC models which were good illustrations of challenging cadastral registrations, I did not find matching cadastral data. In the case of the Lakeside Restaurant, I based the registration on that of another building.

Further data was created by the author in Archicad and Revit (Autodesk).

2.8. Schedule

The project was conducted from late 2015 to the beginning of 2017. It had six main phases and three main deliverables. The three main deliverables included the project proposal, midterm presentation and final report. The project posed a number of challenges, which are discussed in the evaluation section (Chapter 7.1). This meant that although a final report was submitted on the due date, the decision was taken to withdraw it in order to complete further work.

Milestone	Project Proposal	Midterm Presentation	Go No go	Final Report	Go No go	Final Report
Deadline	22 February 2016	29 June 2016		14 December 2016		31 March 2017
Phases						
Initiation	v	V		v		v
Analysis	x	V		v		v
Design	x	V		v		v
Implementation	x	X		v		v
Evaluation	x	X		v		v
Close out	x	X		x		v

3. Literature Review

3.1. The Smart Cities Concept

The twenty-first century is the century of Smart Cities. Cities which are mapped to the last detail and which communicate seamlessly at every level. Smart Cities are mapped in 3D and have buildings designed and managed by Building Information Models (BIMs). The mapping of buildings in 3D BIMs needs a 3D Cadastre or Land Registry to complement it with respect to the legal status of the objects, land and space. While this need has long been acknowledged in the densely-populated Netherlands, the Cadastral map remains based on 2D in spite of the fact that in reality property units include both height and depth. Creating a 3D system, as is being pioneered in several countries around the world, would have many advantages. One relatively simple, cost-effective way to achieve a 3D Cadastre could be to adopt a development workflow which uses information from existing BIMs to create 3D parcels.

We have long been told to 'work smarter, not harder' and the Smart City is a perfect example of that. The concept first came into being in 2008, after the economic crisis hit. It was a time when the world needed to do more with less. A smart city is one which uses information technology to 'work smarter'. The quality, performance and interactivity of urban services is enhanced, costs and the consumption of resources is reduced and contact is improved between citizen and government. An example of how an urban service such as public transport can be improved is through the use of a smart card. This single card, called the 'ovchipkaart' in the Netherlands, allows customers to access and pay for multiple forms of public transport. Individual tickets and having enough small change for the bus fare are a thing of the past.

Figure 7 Smart Cities (IBM.com)

The 'ovchipkaart' is one obvious example of how a smart city works. Figure 7 shows the many other parties which can be brought together by the concept in a general sense.

Figure 8 illustrates the Smart City concept more specifically from the perspective of geo information. It illustrates how the government is the provider of basic data sets as well as the institution which usually prescribes and regulates the standards with relation to the data sets. Industry leverages off these datasets and works within the parameters set by the government to add value. Citizens make use of these added value products and in turn generate further data to be administered by the government.

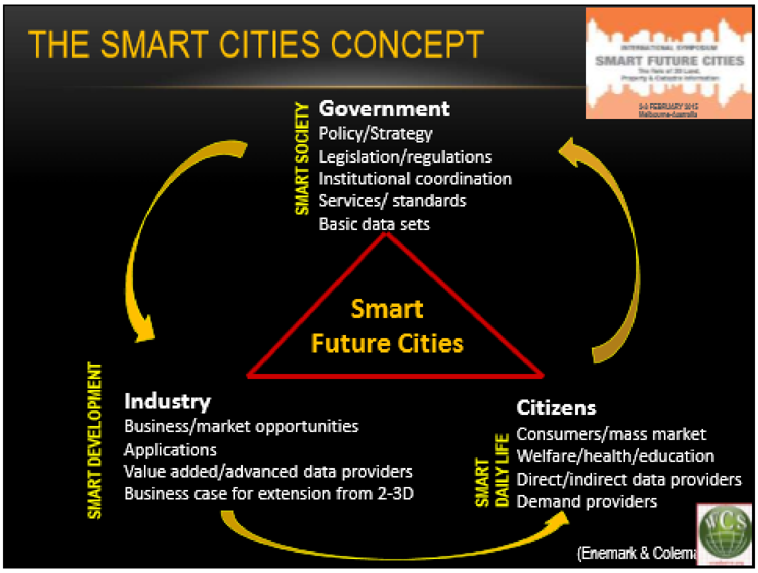


Figure 8 The Smart City Concept (Rajabifard 2015, 5)

3.2. BIM

Building information models are files which can be exchanged to facilitate communication and decision making about a place. While generally a facility or physical infrastructure is a building, they can range from a road, a bridge, a port to a wastewater treatment centre. While BIMs are most commonly used in the design of buildings, they can also be used throughout the lifecycle of the building. The use of sensors means that the physical structure is being constantly monitored. This means that problems such as a leak can be detected and dealt with promptly, sometimes before the occupants of the building themselves are aware of it. This use of sensors is a key part of the Smart City concept, something which underlines BIMs role in them.

3.3. BIM in the wider context: Three definitions of BIM

The Building Information Council of the Netherlands (BIR) and the Dutch BIM Gateway (BIMLoket) define BIM as follows:

- Firstly, as the Building Information Model. This is a digital representation of how a (physical) building (including its facilities) is designed, is realized and how it ends up.
- Secondly, Building Information Modelling places more emphasis on the process, both alone and in partnership. It is about working independently and cooperatively on building projects with the help of exchanging/ sharing digital information models.
- The third meaning, Building Information Management places the emphasis on the information itself; its format, its management and the use and reuse of digital construction information throughout the entire lifecycle of the project.

3.4. The first definition: Digitally designed and managed buildings

Building Information Modelling is the "digital representation of physical and functional characteristics of a facility" (BuildingSmart.org). This means that the design of the facility is fully computerized. The digital model is one which can not only be viewed on a computer screen, as CAD (Computer Aided Design) images have traditionally allowed. For example, the exterior of 210 King St in Toronto is shown as an IFC model in Figure 9. As an IFC model every part of the building has been documented – from the furniture arranged on the roof to panels on the walls (lighting and appliance panelboard Figure 10). Everything in this model has a name and a measurement, and a location. Every element is topologically placed and can be interacted with. This means that analyses can be performed. An analysis or in this context a BPA (Building Performance Analysis) could, for example, determine the energy and water use of a building. In addition cost and fire rating can also be analysed. Figure 11 below illustrates this, and other ways, in which BIMs can be used.

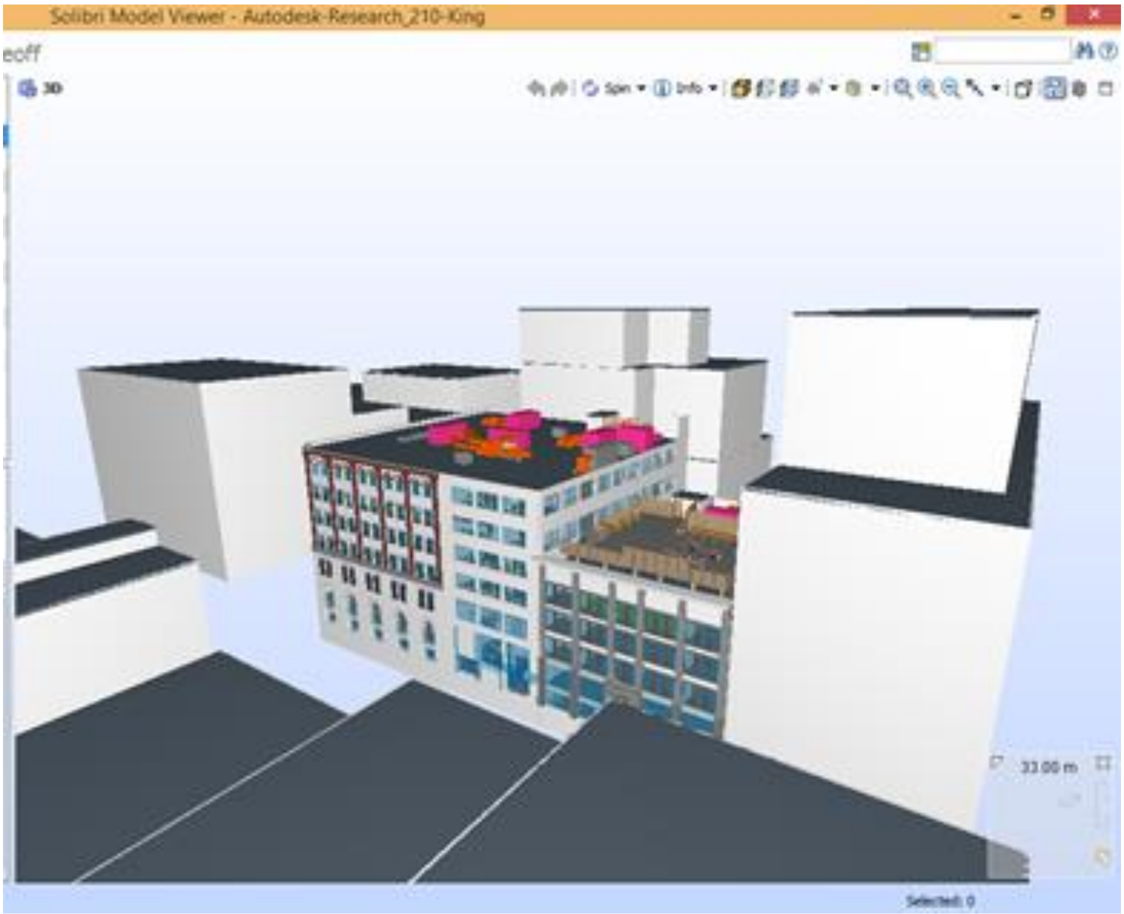


Figure 9 Exterior of 210 King St Toronto (Autodesk Headquarters) as an IFC model

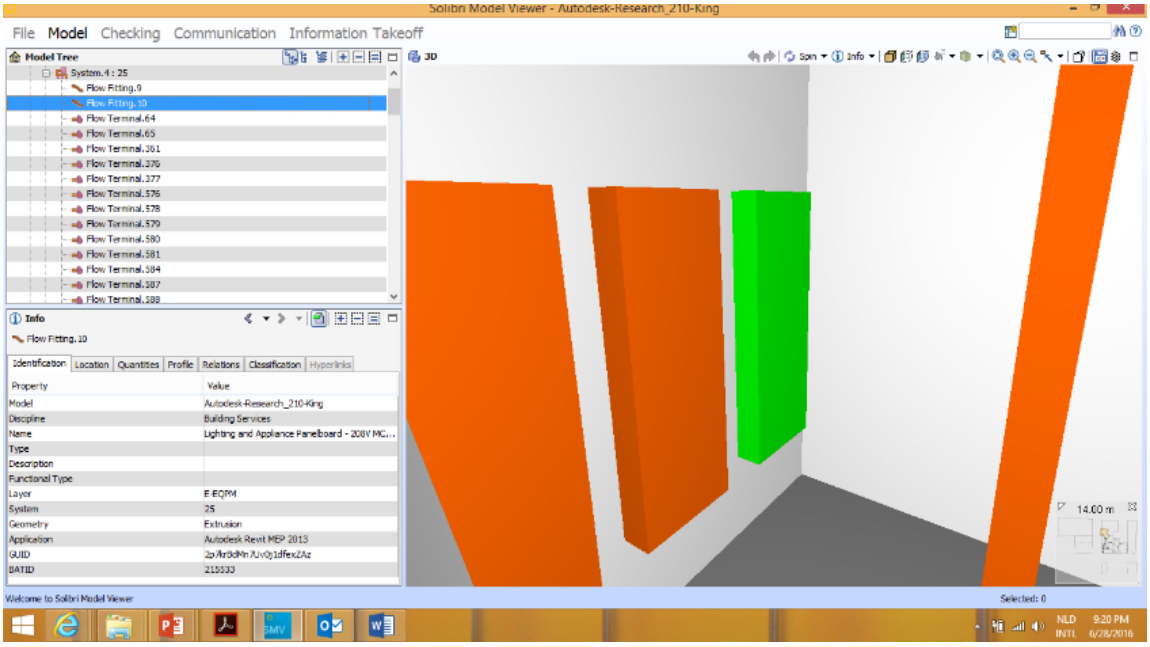


Figure 10 A specific instance of a Lighting and Appliance Panelboard highlighted in green

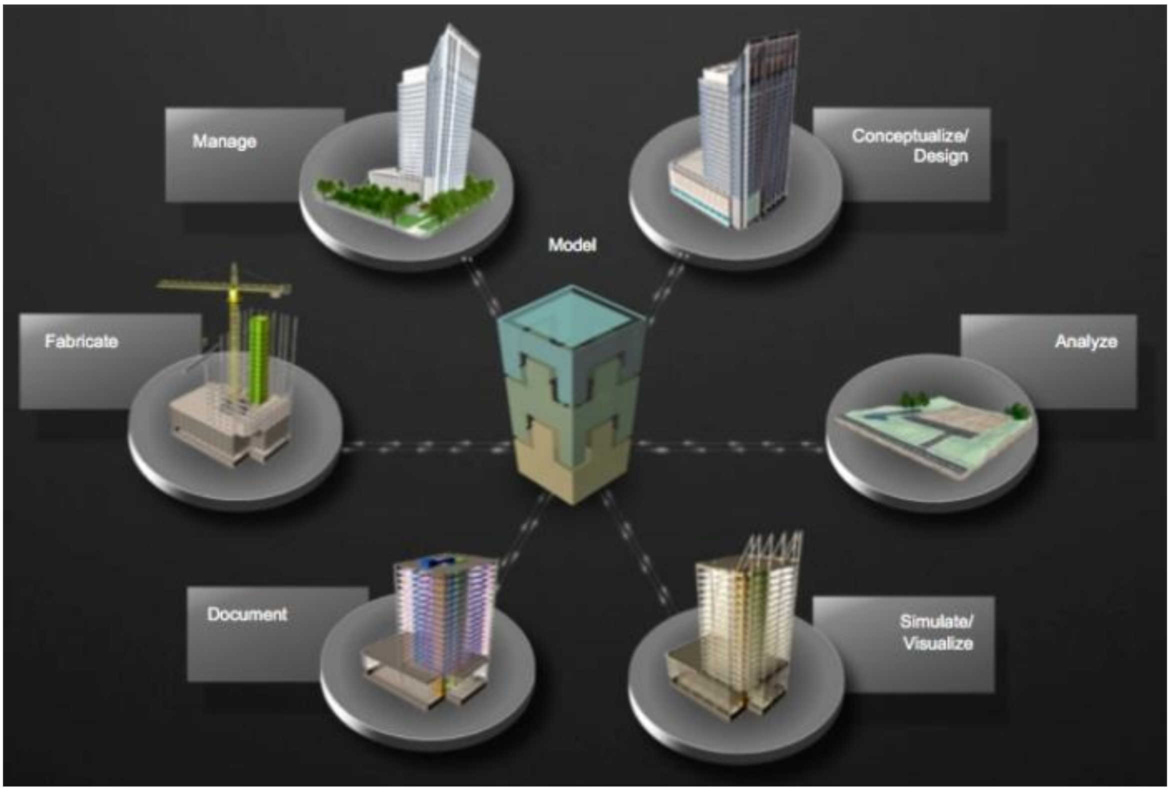


Figure 11 The many ways in which a BIM can be used (Autodesk)

3.5. Non proprietary and proprietary BIM: BuildingSMART

The world of BIM encompasses proprietary BIM, such as the products produced by Bentley (Autodesk) and open BIM, represented by BuildingSMART. BuildingSMART's BIM standards, which are used in this research, are illustrated in Figure 12 below. An open standard is one which can be used and extended by all. It is non-proprietary in that it is owned either by a collective body or by no one and is available free of charge. The use of BIM open standards is steadily gaining ground within the industry. The Dutch

Rijkswaterstaat which manages and builds major infrastructure projects within the Netherlands, for example, became a member in of BuildingSMART February 2016. It should be noted that the commercial products are increasingly supporting open BIM standards.

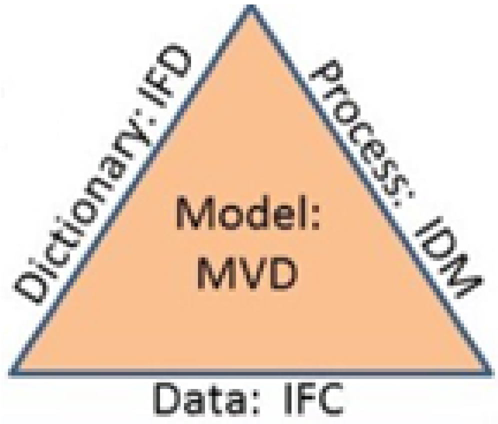


Figure 12 BuildingSMART's main open standards

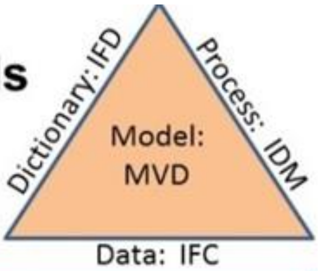
An essential part of the Smart Cities concept is interoperability. This essentially means that all participating elements need to be able to talk the same language. The flow of information has to be unhindered between all of the institutions and other parties involved. BuildingSMART, formerly known as the International Alliance for Interoperability or IAI supports this process.

The two standards used in particular in this article are the Information Delivery Manual (IDM) and the IFC (Industry Foundation Class).The IDM is a methodology used to capture and specify processes and information flow during the lifecycle of a facility (www.buildingsmart.org). The creation and maintenance of a facility, for example a complex construction project, involves many different participants. Knowing what information needs to be communicated between them and when is important. The IDM makes use of Business Process Modelling Notation (BPMN) and templates for Exchange Requirements in order to facilitate this process.

The IFC is a common data schema that makes it possible to hold and exchange relevant data between different software applications (www.buildingsmart.org). It promotes interoperability within the industry. The Lake Restaurant data set, for example, was made using Autodesk's *Revit* and then made available to all using the IFC standard. This standard allows it to be imported back into Revit but into many other applications as well.

Technical Principles: Basic Standards

There are five basic methodology standards



What it does	Name	Standard
Describes Processes	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transports information / Data	IFC Industry Foundation Class	ISO 16739
Change Coordination	BCF BIM Collaboration Format	buildingSMART BCF
Mapping of Terms	IFD International Framework for Dictionaries	ISO 12006-3 buildingSMART Data Dictionary
Translates processes into technical requirements	MVD Model View Definitions	buildingSMART MVD

Figure 13 openBIM standards managed by BuildingSMART (BuildingSMART.org)

The three relevant for this research are the IDM or Information Delivery Manual, the MVD or Model View Definition and the IFC or Information Foundation Classes. The IDM is used to describe processes with the help of an activity diagram format designed over twenty years of experience in the building industry.

3.6. IFC - Overview

Figure 15 provides an overview of the giant IFC model. At its lowest level is the resources layer which has entities used are often used in construction, for example geometry. These entities do not have a unique global id and are never used without reference to another entity. On the next level, the core, entities do have a globally unique id. Entities in the core have the most general entity definitions and are often labelled abstract. An example is *IfcPreDefinedPropertySet.* The next level, is where interdomain exchange is facilitated, and contains entity definitions which bridge disciplines such as *IfcDoor* (part of *IfcSharedBldgElements*) At its highest level, it illustrates the domains, for example the architectural domain and entities specific to them, for example *IfcDuctSegmentType*.

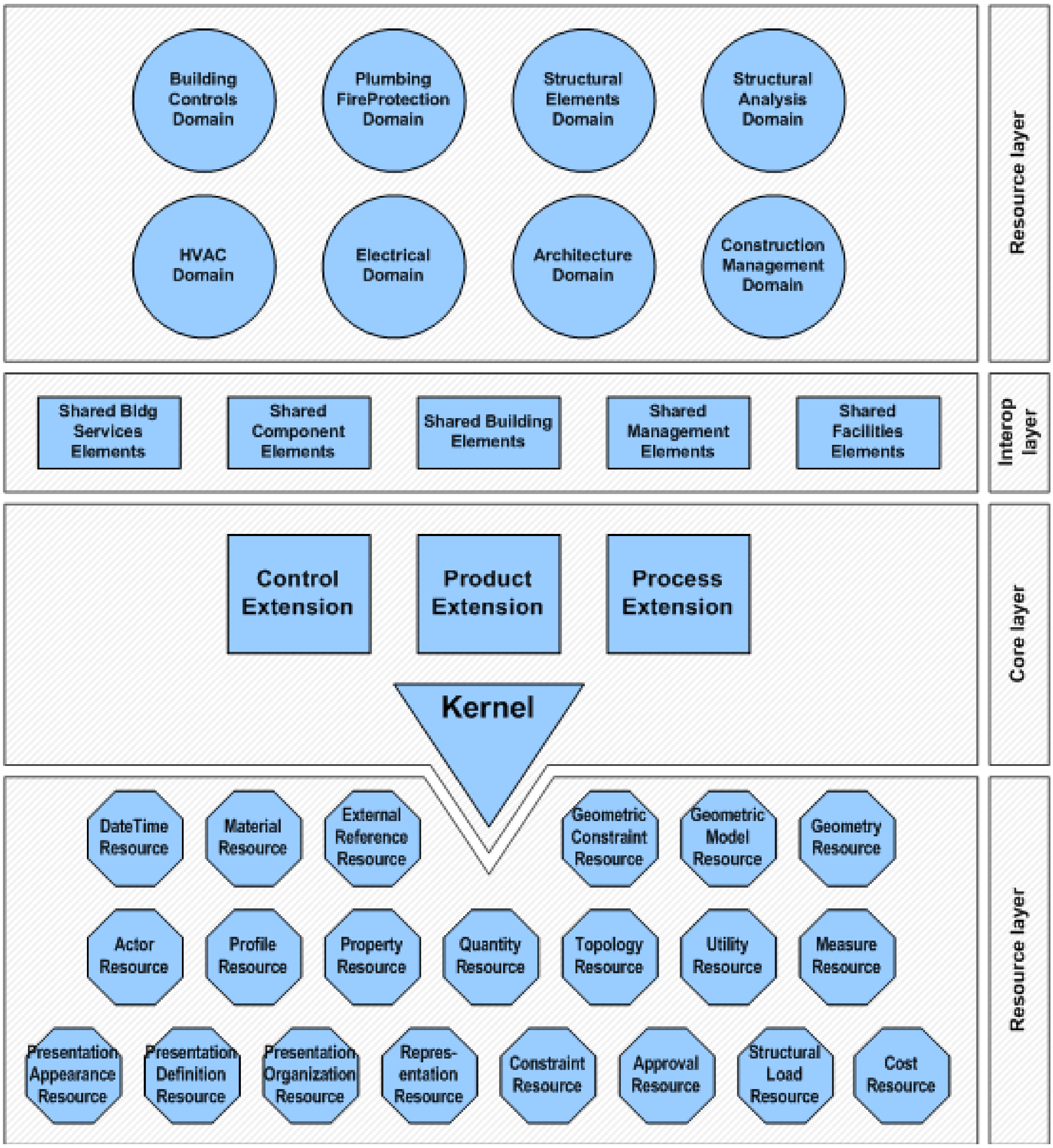


Figure 14 Simplified Concept Model of IFC Data Scheme (buildingsmart-tech.org)

This simplified concept model Figure 14 has been put together as an introduction to the IFC. Someone studying it, however, may come to the conclusion that the model is modular. This is not the case, it could rather be described as a mass of ‘spaghetti’ (Krijnen 2016 Interview)

3.7. IFC – Modelling Language (STEP)

The IFC was defined with the help of ISO 10303 11, also known as STEP or the Standard for the Exchange of Product Data. STEP originated in 1984 and is meant to define standards for general representation and information exchange. Architecture Engineering and Construction (AEC) standards were created within the framework of the International Alliance of

Interoperability, a project of those who had helped create STEP. This is why the IFC includes resources based on STEP and its modelling language – EXPRESS (Steel *et al* 2012).

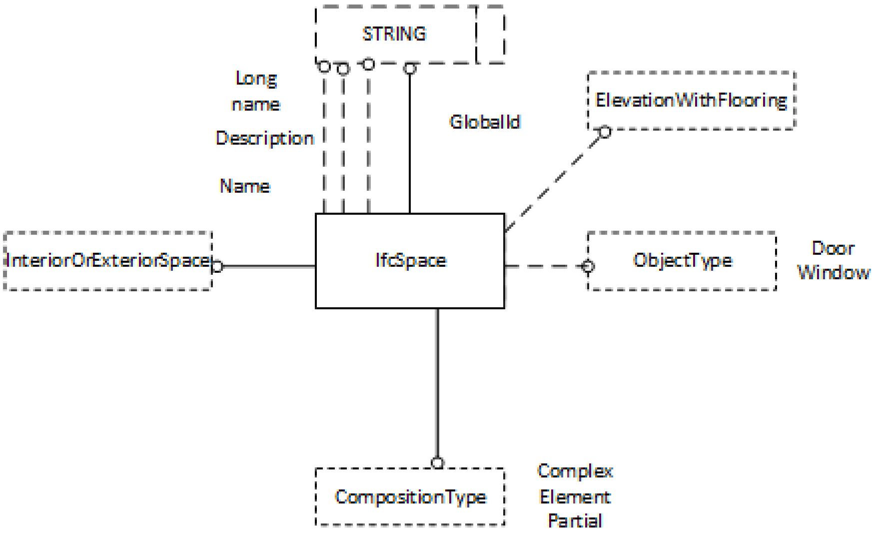


Figure 15 A part of the IFC graphically represented in STEP

Figure 15 illustrates a small part of the IFC visualised in STEP's Express-G notation. In this example, there is one entity which has a unique identity number (Globalid). This is *IfcSpace* which has a unique STEP id (eg#258). This id is within the scope of the file and is valid for a single exchange. It will change if the user project is exported for a second time (Liebich 2009).

IfcSpace serves as the central and supertype entity in this diagram. The rest of the boxes are are attributes of this entity. Some of these are optional, which is denoted by a broken or dashed line and others are not. The global ID, for example is not optional and neither are the composition type or whether the space is an interior or exterior one. The composition type can be defined as complex, a single element or partial. If it is complex, then it is a group or aggregation of similar elements. If it is an element then it is undivided. If it is partial then it is a subelement or part (www.buildingsmart-tech.org). If the composition type is complex then the space can be aggregated into a zone. Interior or Exterior space refer to whether it is an indoor or outdoor space. Express-G visualises the IFC in graphic form in order to explain it. It can also be given in a structured ASCII text file (Liebich 2009) text. This textual form is used for exchange.

The above paragraphs explain what Express-G is. What it is not, by contrast, is a diagram which models the design of a database. While a model view definition can be created by selecting which entities are of most use in a certain situation, for example a Quantity Cost Take-off, what is created is not a view of a database which can then be queried but rather a set of requirements which narrows the scope of a schema. The IFC does not currently have a query language, although there are proposals to do this. In order to build a database from IFC data, STEP files need to be converted into another format. One way in which to do this is to turn to the Semantic Web, an extension of the web based on World Wide Web consortium (W3C) standards.

3.8. IDM

The IDM is a methodology used to capture and specify processes and information flow during the lifecycle of a facility (www.buildingsmart.org). The creation and maintenance of a facility, for example a complex construction project, involves many different participants. Knowing what information needs to be communicated between them and when is important. The IDM makes use of Business Process Modelling Notation and templates for Exchange Requirements in order to facilitate this process. These are explained in more detail below.

3.9. Business Process Modelling the Information Delivery Manual (IDM) way

The Information Delivery Manual (IDM) is used to describe processes with the help of an activity diagram format designed over twenty years of experience in the building industry. Unlike a Gannt (called after Henry Gannt) or a Program Evaluation and Review Technique (PERT) chart which are used by project managers in the business world, this Business Process Modelling Notation (BPMN) is not time based. Its primary function is information exchange within building projects working with the Industry Foundation Class (IFC) specification (buildingSMART Norway 2007). It appropriates ideas from the UML Activity Diagram, UML EDOC Business Processes, IDEF, ebXML BPSS, Activity-Decision Flow (ADF) Diagram, RosettaNet, LOVeM, and Event-Process Chains (EPCs) (BuildingSMART Norway 2007 *Quick Guide*). An extract from an Information Delivery Model (IDM) model is illustrated in Figure 16 below.

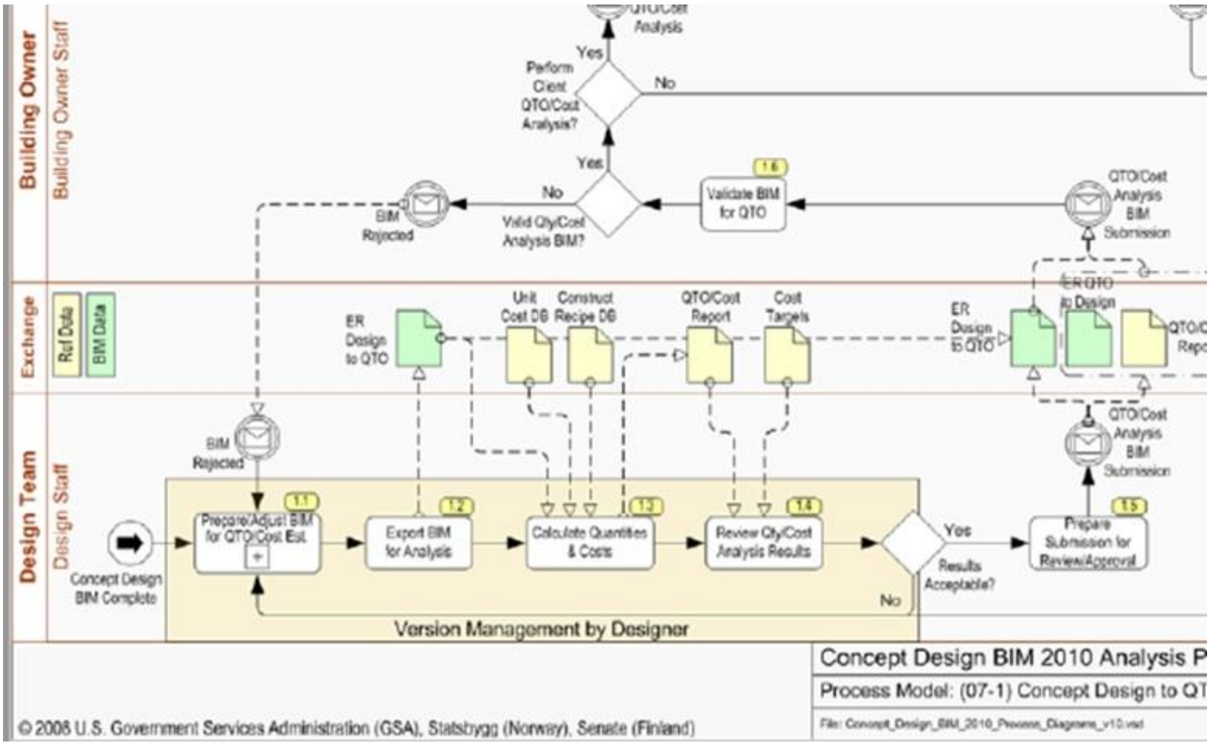


Figure 16 IDM BPMN Example (taken from Beetz 2016)

This extract illustrates a number of features of BuildingSMART's form of process modelling (BPMN). Firstly, in this extract two participating parties or actors are represented – the Design Team and the Building Owner. Their activities occupy two parallel pools, between these pools runs an exchange lane. A further explanation of 5 of the symbols can be found in Table 5 below.

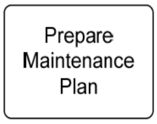
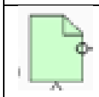
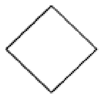
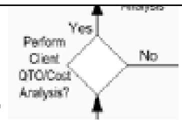
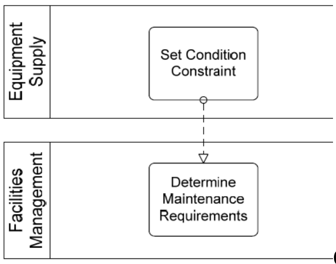
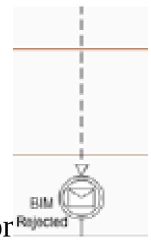
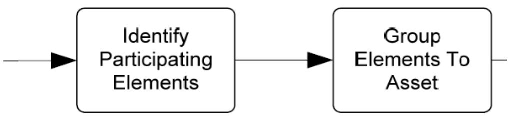
Symbol	Name	Explanation
 or 	Task	An atomic process is termed a 'Task'. The task is the basic unit of the BPMN notation
	Data Object	A sort of 'artefact' which identifies data provision. It occupies its own lane and does not affect the Sequence Flow or Message Flow of the Process.
 or 	Gateway	Exclusive (XOR) data based decision and merging. A choice is made based on a conditional expression (e.g. if X > Y) This decision affects the Sequence Flow
 or 	Message Flow	A Message Flow is used to pass a message, or a set of information, across a pool boundary.
	Sequence Flow	A Sequence Flow is used to show the order that activities will be performed in a Process.

Table 5 BuildingSMART process model notation (Information Delivery Manual's Business Process Modelling Notation) Based on BuildingSMART Norway 2007 Quick Guide

As mentioned above, the IDM was developed for information exchange and worked to break the IFC down into manageable chunks. In contrast with project management models such as a Gannt chart, it is not time based but rather sequenced based. For example, it is important that the architect receives a building permit before he begins building, but not the exact date that that needs to occur. How this is exchanged is specified in an Exchange Requirement document, as illustrated in Figure 17. The template in Figure 18 has been filled in by the author to illustrate the exchange of a fictitious Legal Space document.

In this exchange requirement template, headings that should be retained are not surrounded by <...>, not in italic text and are not contained in a comment box(such as this box).
Elements that are within <...> should be replaced by user defined or developed text
Elements in italic and marked, coloured comment boxes are for guidance and should be removed from the final version.
Delete this box from the final version.

Exchange Requirement

Name	**<replace with name of exchange requirement without er_ prefix>**

Identifier	<give the exchange requirement a unique identifier>

Change Log		
<yyyy-mm-dd>	<action>	<author email address>

Project Stage *<omit ✓for not relevant stages and*	0	Portfolio requirements	✓
	1	Conception of need	✓
	2	Outline feasibility	✓
	3	Substantive feasibility	✓

Figure 17 Section of an Exchange Requirement Template.

Exchange Requirement

Name	<Exchange Cadastre (Legal Space)>

Identifier	<xxx>

Change Log		
<2016-06-29>	<Created>	<jo@cadastre.nl>

Project Stage	0	Portfolio requirements	
	1	Conception of need	✓
	2	Outline feasibility	
	3	Substantive feasibility	
	4	Outline conceptual design	
	5	Full conceptual design	
	6	Coordinated design and procurement	
	7	Production information	
	8	Construction	
	9	Operation and maintenance	
	10	Disposal	

Overview

Scope
<The scope of this exchange requirement is to enable the exchange of information related to 3D legal spaces which must be defined within BIM models before being lodged with the Cadastre>

General Description
< This exchange requirement allows for the provision of information at various stages during the design process including outline conceptual or sketch design, full conceptual design and coordinated design. The information provided at each stage is essentially the same.
However, the level of certainty regarding geometry required will increase at each stage allowing greater certainty in legal space definition.>

Information Description
<Information required concerning the definition of legal spaces includes:

- Common property
- Ownership spaces eg apartments>

Figure 18 Exchange Requirement Document

Process models are not only useful during the project itself, they can also be used to analyse the process after the project has finished. For example, how could the building have been built more efficiently and what could be improved?

3.10. Model View Definition

The third standard illustrated in Figure 12 is the Model View Definition. The model view definition is used to narrow the focus of the IFC to a subset. This subset includes a set of implementation instructions and validation rules and is published in mvdXML (buildingSMART.org). Examples of how a Model View Definition can be used are for human circulation and security analysis, energy performance analysis, spatial program validation or quantity takeoff to enable cost estimating (Weise 2009). Figure 19 illustrates how a Model View Definition stems from the requirements definition established through the creation of a Business Process Model.

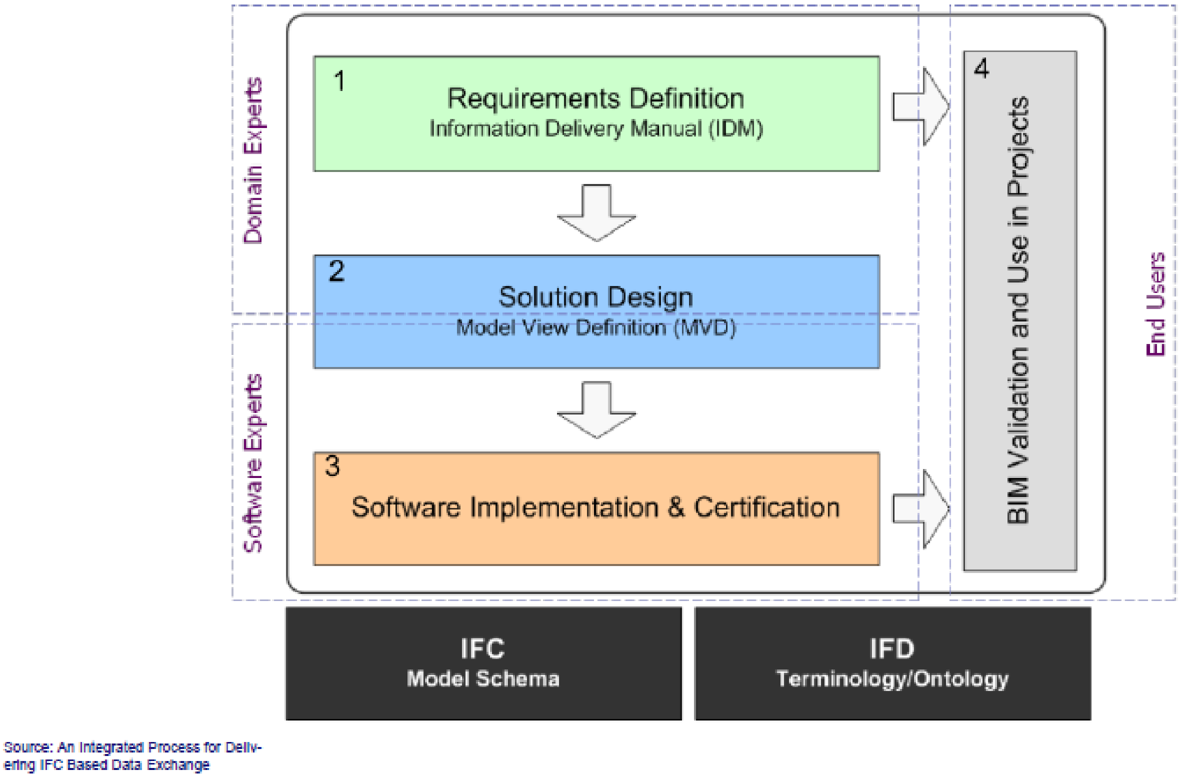


Figure 19 how the standards work together (Beetz 2016)

3.11. BIM & City GML

This thesis looks at the interface between Land Registry Systems, which are traditionally the field of Geographic Information Systems (GIS) and BIM

BIM	GIS	Example from *Kadaster*
3D Geometry	Still emerging from 2D Geometry	2d drawings
Mostly file based and exchanged as files	Server-focused approach	2D drawings and other registrations can be accessed online
Intense Semantics: decomposition and specialization of objects in the model (IFC has around 650 entities)	Far fewer semantics	See Table 9 Mapping the IFC to the LADM
Relationship between objects is of strong importance	Relationship based on co ordinates	*Kadaster* makes use of a spatial reference system

		rather than localised co ordinates
Used for new buildings and structures	Existing data or policies	*Kadaster* has been in existence in some form or another for a long time

Table 6 BIM and GIS compared with examples from the Kadaster (based on Berlo et al 2011)

The topic of integrating BIM with GIS is not new. Table 6, for example, is based on a project - the BIMServer – which took place 5 years ago. Comparatively little work has been done with relation to integrating BIM and a 3D Cadastre. More work, by contrast, has been done on integrating BIM and City GML.

CityGML or City Geographic Markup Language, is an open GIS standard used to store and exchange virtual models of whole cities. By comparison, the IFC is used to store and exchange models of individual buildings and structures within and around these cities. CityGML originated in Germany, where it is already in widespread use. It has also been extended for use in the Netherlands, where it is also a national open standard.

Figure 20 compares the IFC's solid geometry with CityGML's use of bound surfaces. In the picture on the left, the walls and floor slab are solid separate entities. In the picture on the right, by contrast, the walls are hollow and are represented by bound surfaces.

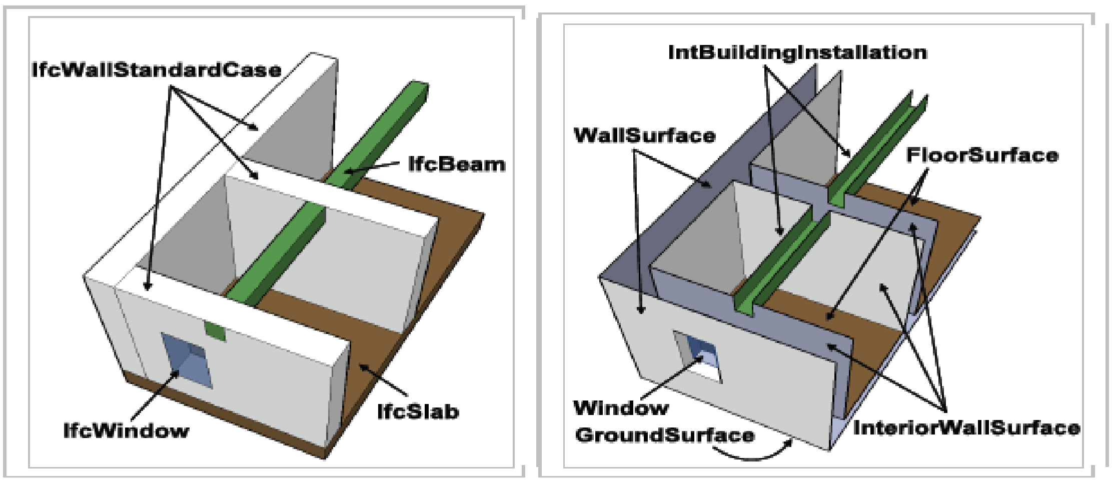


Figure 20 the approach of IFC and City GML compared (Nagel 2007)

3.12. Land Registry Systems

Land administration involves maintaining a cadastral mapping agency and a Land Titles office or Land Registry. In some countries these roles are maintained by a single organization, in others they are separate. These organizations involved are considered the governmental authority in each region or country where they administer land. As such they have a pivotal role in the Smart City concept as a coordinating institution. It makes sense, therefore, that where possible its data should be managed and maintained through the use of semantically-rich 3D Models.

It makes sense from a number of perspectives. Firstly, it would bring it in line with other developments in this field, for example BIM. Not only would it bring it in line, but reusing the rich content of BIM models based on open exchange standards would save on costs and provide an interoperable result. For instance, geometry could be reused.

Secondly, a considerable increase in property values, both public and private, mean that a clearer picture with relation to their property rights, restrictions and responsibilities – the 3D RRR's of the Cadastral world (Aien *et al* 2011) – is needed. For example, a 3D spatial representation derived from a BIM of an apartment spread across multiple rooms but belonging to one owner, could bring clarity to ensuing legal issues.

3.13. BIM and a 2D Land Registry System Compared

Table 6 below compares BIM and a 2D Land Registry System. While including details of the physical space may be useful to a 3D Cadastre, the emphasis is on legal space and not physical space. All of the other points of comparison, however, are of interest to a 3D Cadastre. Incorporating BIM files would allow the cadastral Map of Legal Spaces to become partly, if not wholly, open to queries. This is partly, as other parts of the map without associated BIM files would also need to become 3D and able to be queried. Centralising the many text documents associated with the Map of Legal Spaces in the manner of a BIM file would also save time and money.

BIM	**2D Land Administration System**
3D	2D
Fully digital	2D drawings
Allows spatial queries eg volume calculations	Queries have to be processed manually
Centralised information	Spread over many different documents
Physical Space	Legal Space

Table 7BIM and a 2D Land Administration compared.

3.14. A second information standard: the Land Administration Domain Model

While BIM models physical infrastructure, the Land Administration Model or LADM works from the perspective of legal spaces. Its focus is on the 'rights, responsibilities and restrictions which affect land or water and that land's geometrical components' (Lemmen 2015). The LADM ISO 19152 is an open standard which has been adopted by the International Organisation for Standardisation (ISO). It is illustrated in Figure 21 below.

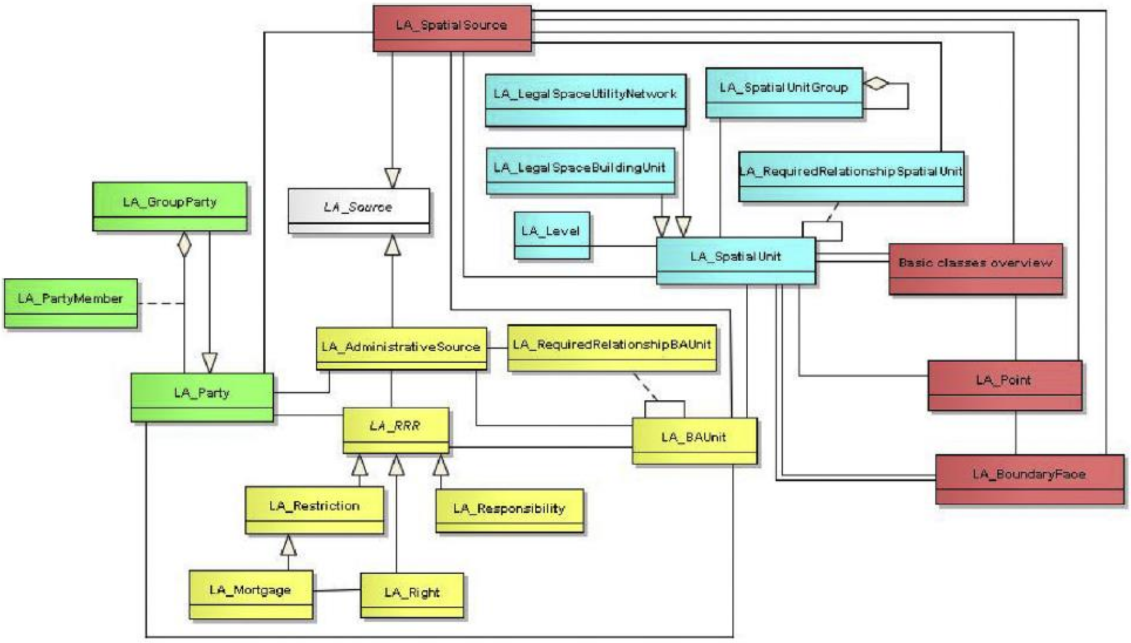


Figure 21 The Land Administration Domain Model (LADM)

The LADM is a conceptual or information model completed in Unified Modelling Language (UML) but is not a data product specification and has no associated exchange format. Thus, it does not detail how to deal with what it describes in practice, nor does not provide any region-specific solutions. For example, it does not provide any encoding during exchange using XML or data storage in a database. It is a 'descriptive standard' rather than a 'prescriptive standard' (Lemmen *et al*, 2015).

The LADM is inclusive in both senses of the word. To begin with it tries to include everything. It can embrace property descriptions from something as detailed as a BIM to a textual description such as 'from here to the edge of the river'. It includes utility networks such as gas pipelines, water pipelines and electricity networks. In addition, it also encompasses the many textual details which were once separate papers for example mortgages.

Secondly, the LADM is inclusive in the sense that it tries to cater for every type of society in the world in a fair and equal way. This has already been illustrated by the fact that property descriptions can be completed with a BIM or a sentence such as 'from here to the edge of the river'. A technologically advanced society such as the Netherlands may use a BIM whereas a tribal society may use the second option. In the same way, the tribal society may be group owners of the land. Their collective rights would be recognized by the fact that LA_Party can be a person or an organization. If desired, they could have individuals in the tribe included in the registration through LA_PartyMember.

The LADM is an international standard. Land Administration Systems vary widely throughout the world. The LADM is meant to serve as a framework which can be added to as needed, dependent on the country which implements it. Figure 22, for example, shows a small sample of how Poland has integrated and extended it.

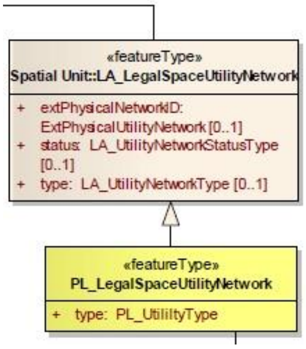


Figure 22 A small section of the Polish Cadastral Domain Model. The LADM has been extended for the Polish context. (Gozdz et al 2014)

As mentioned above, the LADM is a conceptual model and does not currently have an associated exchange format. When this is decided, it will be from a range of choices such as LandXML, InfraGML or City GML.

3.15. Legal Spaces

A key emphasis of the LADM is legal spaces. This term encompasses two broad areas. The first area is that of geometrically-defined legal spaces, the second area is the rights, responsibilities and restrictions associated with it. The LADM UML class model illustrates this with its clearly defined administrative package which incorporates the RRR's (rights responsibilities and restrictions) and separate spatial unit package. While the administrative package records items such as the name of the owner recorded as a CharacterString or the proportion they own (share: Fraction [0.1]), the spatial unit package is concerned with the physical object itself. Traditionally in western cultures, this has been a black and white line drawing. The LADM, however, encompasses not only this possibility but many others, for example a sketch or a single point. (Lemmen *et al* 2015).

3.16. Legal Spaces: Right of ownership

The right of ownership (*eigendomsrecht*) rests on the idea that, although the parcel is documented as a 2d line drawing, the owner owns the area above the parcel up to infinity and below to the earth's core (see Figure 23). The owner also owns the permanent structures on that plot of land.

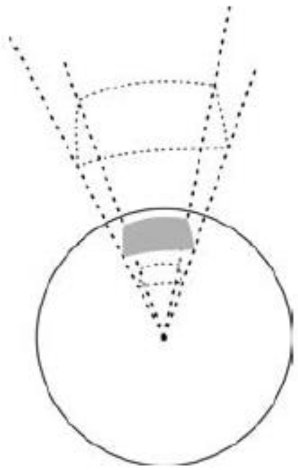


Figure 23 Illustration of Vertical Accession. The landowner owns the column above and below their land reaching up to infinity and down to the earth's core. (Stoter et al 2004)

Of course, in reality there are caveats to this. By law, the owner of the land does not control the airspace above their land (*Luchtvaartwet*), nor do they control the mining rights. Two Dutch laws relate to these mining rights the *Mijnwet 1810* and the *Mijnbouwwet 2003 (*Stoter *et al* 2004*).* In addition, local planning laws also impose restrictions on what land owners can build on their land. These, however, do not relate to cadastral registration in the Netherlands (Stoter *et al* 2004).

The owner of a plot of land is the owner of a column reaching up to infinity and down to the earth's core as illustrated in Figure 23. As stated in the previous paragraph, there are caveats to this, such as airspace and mining rights in addition to the overlook illustrated by Figure 3 A further caveat is that all constructions fixed to the land belong to the owner by vertical accession, unless they are part of another person's property.

Encroachment onto another person's property is allowed if that owner agrees to it. It is, however, not registered at the *Kadaster* and does not have legal status. This means that when the property changes hands, the new owner may no longer have rights to what was once part of the property. In simple terms, after the property has changed hands the extended balcony room may have to be removed.

3.17. Legal Spaces: Limited ownership rights

One way to solve this problem is to evoke the right of superficies (*opstalrecht*).This is a real right to own or to acquire buildings, works or vegetation in, on or above an immovable thing owned by another"(Stoter *et al* 2004). In this case, a text document grants the owner of a construction rights in spite of the fact that they do not own the land. Unfortunately, there is no geometry to support this claim so the actual spatial extent of the property is unclear. An example of this would be a building positioned above a pipeline. The land above the pipeline belongs to the council, but the building above it to someone else. The clarification of limited ownership rights would be greatly aided by the introduction of a 3D Cadastre which would include geometry to visualise the situation.

3.18. BIM and Legal Spaces

While BIM could be used to provide the geometry for a 3D Cadastre, the spaces themselves would be different from those defined by the BIM. While BIMs work with complex physical spaces, for example the rooms, corridors, walls and floors of a building, the legal space needs to work with only one space for a single property. This is in spite of this space containing a number of physical spaces (rooms) or parts of physical spaces (to the middle of the wall space). In this new legal space the boundary surface binds and defines the size of the spatial unit, and thus the right that an entity such as an owner can claim on it. This new legal space can be amply represented in open BIM exchange models.

A further example is the space which might need to be left around a pipe. Imagine a pipe situated at the bottom of someone's garden. The title deed specifies a restriction. This restriction is that nothing can be built over the pipe so that access can always be gained to it. Thus the legal space is not the pipe itself, but an extended space around it.

At this point, however, the world is still working out exactly how a 3D Cadastral model should most efficiently be put together within the constraints of the Land Administration Model ISO 19152. Moving across to 3D also provides a unique chance for a 'complete rethink' (Rajabifard 2014) of the system.

3.19. Literature Review Conclusion

The time is ripe for a 3D Cadastre to be designed as part of the complete development lifecycle of the Smart Cities concept. This Cadastre would be made within the context of other 3D developments such as the LADM and BIM and would therefore be interoperable. It would offer better documentation and design and provide better communication between all parties from industry government and the citizen body. One way to achieve this aim might be to reuse data from BIM models as input to specific 3D parcels. Crucially, if this could be done efficiently it would mean significant savings in both time and money.

3.20. Activity Diagram

This conceptual diagram was created after the literature review had been finished and before any technical work was completed. It shows the desired workflow.

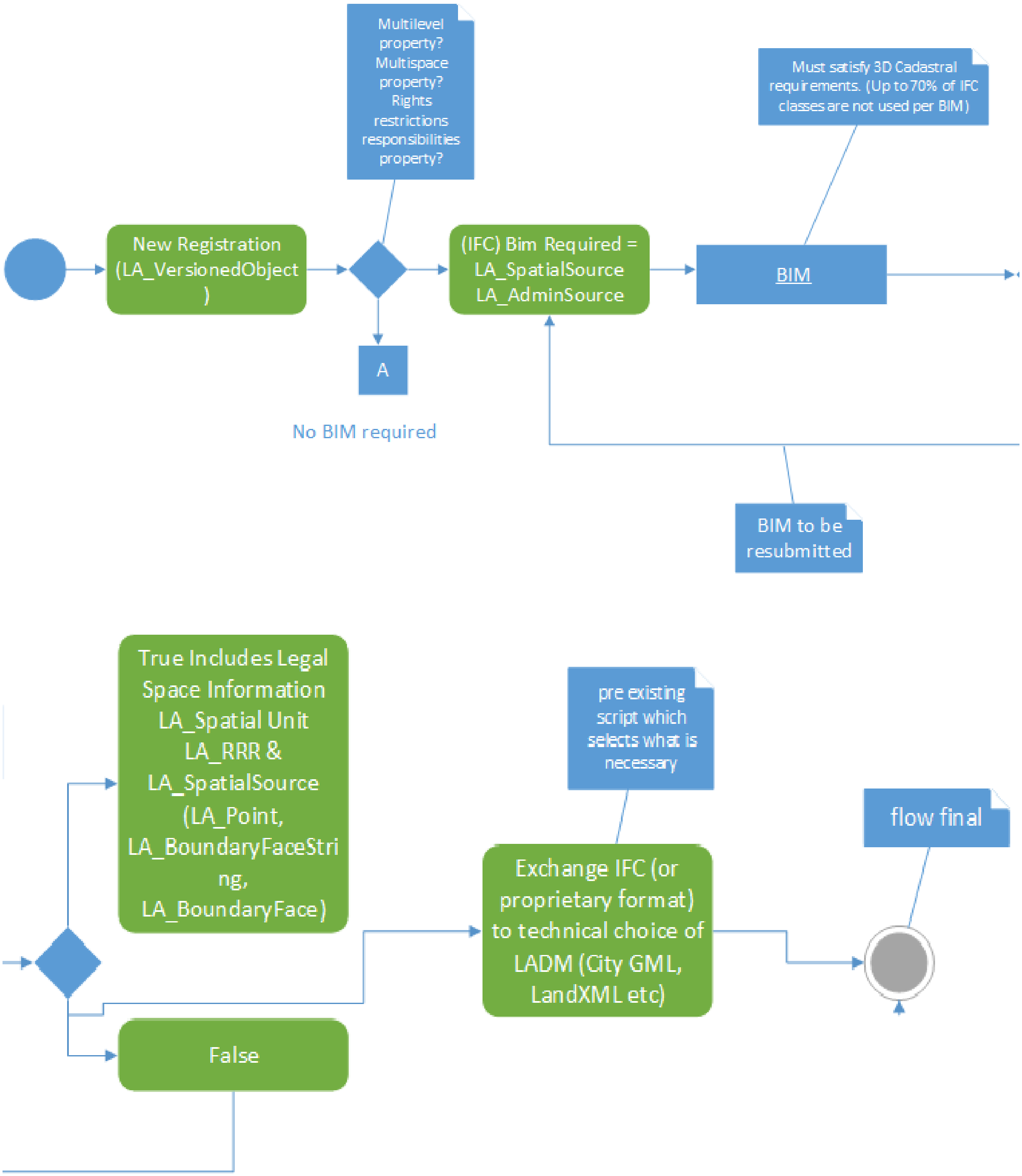


Figure 24 Information House: Buildings

4. Proposed Data Model

This chapter proposes a data model for a 3D Cadastre within the framework of the LADM. It begins be defining the requirements for a model and then looks at the best exchange format for the model maps the semantics of the IFC to the LADM and then illustrates this with an express diagram.

4.1. Model Requirements: the 3D Cadastre Perspective

The data model has a number of requirements from the cadastral perspective. These requirements are particularly relevant in three different cases:

1. When property owned by one person encroaches onto another's, for example the cellar of one house which widens out under the house of another or an oddly-shaped building which straddles a road see Figure 25. The rights to this building can be established through the right of superficies or of easement (Stoter et al 2012). If these rights are not registered with the authorities (for example as in Figure 3 then they do not have to be visualised.

Figure 25 Building (Malietoren) above the Utrechtsebaan (A12) The Hague source:www.wegenforum.nl

2. this again involves multi-level use rights and is similar to the situation outlined in 1. In this case, however, the situation is complex. This means that it involves more than one instance of superficies. It could involve, for example, a building built above another building but with its sewerage pipes running beneath it. A further complication could be an easement for allowing enough fresh air to reach the building. (Stoter *et al* 2012) The building registration can be complicated even further if space within the building claiming the right of superficies is occupied by easements from the building which officially owns the land. This dilemma is illustrated by the Lakeside Restaurant Use Case and discussed in Chapter 6.3.

3. Apartment buildings. Under Dutch law separate drawings are already required to be submitted for apartments however these cross sections quickly become inadequate if separate apartments differ in shape. These differences in shape can include the apartment being spread over different floors, for example one which has been created

within a pre-existing building, or an apartment which owns a parking area underneath the building. The size of the apartment complex can also be a factor, the larger the building the more useful the 3D registration would be.

Figure 26 An apartment created within an existing building with different-shaped spaces spread over a number of floors – the top right hand picture shows the first floor and the bottom right hand the ground floor. Funda.nl

The three scenarios above are the ones where 3D registrations would be most useful. The LADM however, covers as wide a range of scenarios as possible, not just those described above. Ideally, every one of these scenarios would be included in a topological database. With this in mind, the requirements list below includes volumes unbounded either at the top or bottom, these would become parcel columns. These parcel columns would represent the original 2D parcels illustrated in Figure 23. The list does not try to account for the fact that many 2D parcels in the current system are unclosed. This means that there is a gap in one of the lines which form the boundary of the parcel. In the future, these non-manifold parcel boundaries will also need to be included, as will non-exact mathematical presentations (Thompson *et al* 2012).

Requirements	
Label	What it does
Zoom Pan	Be compatible with a number of implementations so that it can be uploaded. This would then enable the model to be rotated using pan and zoomed in and out of by using the software. Examples of this software include Autodesk's Revit and Archicad

Different Colours	Use of colour to highlight who owns what, colours could also be used to illustrate different restrictions such as overlook
Bounded closed topological volume	Topological volumes allow the legal spaces to be connected up together without overlap and the creation of an overview
3D complex ID	Legal space related to one or more ground parcels with separate unique indices to connect it up with different rights
Location information (co ordinates)	Legal spaces positioned both by local co ordinates and the national height datum system on a map rather than referenced to physical markers as in the current Dutch system.
Different 3D representations	Different views on the same 3D design drawings for example artistic impression (3D drawing), respective view 3D legal spaces, vertical cross section, floor plan of first floor
Different volumes	Incorporates traditional parcel columns in addition to volume parcels
Data checked for validity	Geometrically and topologically correct (no non manifold objects, closed volumes) and no overlap but not for how accurately it represents the building – this would be left to the owners as in the current system
Geometry - Polyhedron and 3D representations open at the top and/or bottom	This is how the volumes would be stored in a database
Adheres to NEN2580, 2007	This is a Dutch national standard used in relation to measuring volumes and areas within constructions
Web Server based	This would allow queries to be made from a variety of sources including the organisation itself and individuals

Table 8 Requirements of a Dutch 3D topological Cadastral database based on Stoter et al 2012, Stoter et al 2016, Thompson 2016

4.2. What Would be the Best Existing Model to Base a 3D Cadastre on: LandXML and InfraGML

LandXML as an electronic data transfer standard which captures, validates and visualises civil engineering and survey measurement data. It came into being in 1999 in the United States of America in cooperation with Autodesk. The LandXML user community currently consists of 669 organizations with 762 members in 41 countries and the standard is supported by 72 registered software products (LandXML.org) Importantly, it is an industry standard which has been adopted or incorporated into a number of national standards, for example Australia’s e-plan. It is a non-proprietary standard which enables long term data archival (LandXML.org)

LandXML is not, in contrast to the IFC and CityGML, an open international standard registered with the OGC. Furthermore, while it can be used to exchange data concerning pipelines, roads, cadastral parcels and land use; buildings are represented not as volumes but as footprints. This means that while it is useful for open country, it is less useful for built up areas or for building models which incorporate both. In addition, LandXML does not have any formally published documentation, user guide, requirements definition, or underlying conceptual model (www.opengeospatial.org).

A new standard which incorporates LandXML is currently being developed by the OGC, InfraGML. This standard would aim to improve on the foundations already laid by LandXML, although intially focussing on survey, alignments and land parcels before branching out into pipe networks and other areas. InfraGML would work in close conjunction with buildingSMART in their development of Infrastructure-based IFCs while making the standard be more easily integrated with TransGML and CityGML.

InfraGML, with its emphasis on transportation and pipe networks is of real interest to a 3D Cadastral database. The bridges and tunnels which form part of a transportation network also need to be registered and pose many of the challenges to a 2D cadastre that the three cases outlined in Chapter 4.1 do. The inclusion of the underground pipe network in a 3D cadastre would also be a very useful addition, particularly as many of the more challenging 3D use cases have pipes beneath them with their own accompanying rights and restrictions. As the Dutch *Kadaster* already has a department devoted to pipe networks, making use of this data could be done within the same organisation. Furthermore, the fact that buildingSMART is working in close conjunction in the development of the standard would facilitate its integration into a topological overview of buildings based on the IFC standard.

InfraGML, however, is still being developed at the time of writing. On top of that, transportation and utility networks are beyond the scope of this thesis. This means that it did not fulfil requirements and was not considered any further.

Figure 27 An example of a road stored and visualised in LandXML (LandXML.org)

4.3. What Would be the Best Existing Model to Base a 3D Cadastre on: CityGML

As discussed in Chapter 3.11 and Table 6 CityGML is an exchange and storage format which is in many ways close to what a 3D Cadastre requires to come into being. This standard used to model cities has many advantages. To begin with, CityGML does not use CSG, or Constructive Solid geometry, a key feature of the IFC. This means that it is easier to adapt to current cadastral databases systems throughout the world. The majority of the world's Land Registry systems are drawn as 2D line-based parcels using the boundary representation which is characteristic of Geographical Information systems. Any database which works with Land Registry systems, such as the Dutch *Kadaster*'*s* database stems from the world of Geographical Information Science rather than that of the construction or buildings (BIM). CityGML is also a product of the world of Geographical Information Science.

Secondly CityGML is topological on a wide scale, therefore giving an overview not just of buildings but of entire urban areas. This closely resembles the *Kadastrale Kaart* (Map of Legal Spaces) see Figure 1. It also allows queries and analyses to be made over a broad area, for example a disaster analysis which calculates which buildings will be most affected when a bomb is exploded. The discovery of unexploded bombs from World War II is a common occurrence in Germany, and often they cannot be dealt with in any other way.

Thirdly, CityGML is represented by bound surfaces, which would be a good place for a 3D Cadastre to begin. This is in spite of the fact that in reality buildings are often far more complex, with open outdoor spaces such as roof-top terraces or balconies protruding from high rise buildings.

In contrast with IFC models, CityGML buildings do not need to be generalised. The models at Level of Detail 2, which are footprints extruded from a building footprint or floor plan, are simple enough. The fact that these can be extracted and extruded from an aerial photo is a further advantage, saving on labour and costs.

One aspect that CityGML does not have in common with a Land Registry database is that it is not server based, working rather with file exchange. This means that files need to be sent from person to person, rather than being accessible by many from one central point or server.

Another advantage of the CityGML exchange format is that the data model is modular, which would facilitate the addition of a legal space or Cadastral extension to it. This is something that could well already in progress.

Lastly, CityGML models are based on numerous local co-ordinates. This comes courtesy of its Geographical Information Science background. Models based on the IFC, by contrast work with one local coordinate and many Cartesian points which leverage off it. This could be useful, for example, when incorporating survey points into the system. Survey point information is represented in the LADM by LA_SourcePoint.

As can be seen above, CityGML would have many advantages as a format for building a topological map of legal spaces. Unfortunately, few models of the specific use cases listed in Chapter 4.1 exist or at least not at the level of detail required. This has led the CityGML community to look at automatically generating Level of Detail 3 and above models from IFC datasets themselves (Donkers *et al* 2015).

4.4. What Would be the Best Existing Model to Base a 3D Cadastre on: IFC

The GIS and BIM worlds have traditionally been separate ones, the one modelling large areas and the other focusing on separate buildings. The people who work in the world of GIS have traditionally begun as geographers or surveyors, those who work with BIM as architects. While BIM, or more specifically the IFC, includes points, lines and polygons it focusses largely on other forms of representation.

While perhaps a less obvious choice than CityGML, the adoption of IFC as an exchange and storage format would have many advantages. To begin with, just as CityGML, it can be modelled in a topological way. It does in fact, provide a wide variety of topological formats ranging from topological thermal boundaries (IfcSpace 2nd level boundaries) to Nurbs (Non-uniform rational B-spline). Nurbs are represented in IFC4 by IfcAdvancedBreps. The IFC, however, has more traditionally worked with Facetted Boundary Representation (IfcFacetedBrep) based on triangles.

Although CityGML is developing, for example with the addition of IndoorGML, the IFC provides and will probably continue to provide far more ways to model in 3D. It counterbalances CityGML's ability to provide an overview with the ability to model in great detail and in different ways. For instance, while CityGML volumes are restricted to bound surfaces, the IFC encompasses open shells. To take the example further, CityGML is constrained to representing an outdoor terrace or balcony as a closed volume. By contrast, the IFC can represent it more accurately as an open volume. These open spaces or half-spaces can be represented and incorporated into a coherent whole without losing the ability to query the model.

One challenge that the IFC faces is that its great detail is only partly required by a 3D Cadastre. This means that models may need to be simplified or generalized and that in order for the IFC to become a usable standard, a well-defined subset of the capabilities of IFC needs to be selected. For instance details of wall coverings, plumbing or even indoor furniture is of little interest to a 3D Cadastre but is something which is often included in a 3D model.

Both BIM and CityGML can be accessed from a server. BIM is commonly used in an interactive editing environment with many parties involved. This is to enable all parties involved in a project to access the same file. For example a team working on a complex, mid-city high-rise may all have access to the same BIM. If a member of the HVAC changes the position of a heater in a room the model is then updated and the rest of the team are able to see where it has gone. By contrast, CityGML files are exchanged 'as-is'.

One disadvantage the IFC faces, is the fact that it is based on a relatively inflexible modelling format. This format is described in Chapter 3.7. Unfortunately, changes to the classes of the actual model take years. In addition, changes make the model too difficult to implement. It is, therefore, preferable to work within the many options already available. One of these options is property sets.

A property set extends the IFC model without changing it. It is created within a framework for user defined information. This framework is sometimes called a meta model. A property set is a container class which holds properties within a property tree (buildingSMART-tech.org). A property set becomes an instance, rather than a class, and can be defined at a project or a regional level. A further option is to work with common or predefined property sets (p_set) which are included from IFC2*3 onwards.

4.5. Mapping the IFC to the LADM: Semantics

IFC Entity Type	*LADM*	*LADM Geometry*
IfcProject	LA_SpatialUnit	
IfcSite	Survey::LA_Point Spatial Unit attribute reference point	GM_Point
IfcBuilding		
IfcBuildingStorey		
IfcProduct		
IfcSpatialStructureElement		
IfcSpace	LA_LegalSpaceBuildingUnit	
IfcClosedShell		
IfcOpenShell		
IfcFacetedBRep		
IfcConnectedFaceSet	LA_BoundaryFace	GM_MultiSurface
IfcFace		
IfcFaceOuterBound		
IfcPolyloop	LA_BoundaryFaceString	GM_Multicurve
IfcPoint		
IfcCartesianPoint	LA_point	GM_point
Optional: IfcZone	LA_LegalSpaceBuildingUnit	
IfcPropertySet		
IfcIdentifier	LA_LegalSpaceBuildingUnit Attribute:unitNum	

Table 9 Mapping the IFC to the LADM

The above table illustrates how the semantics of the IFC can be mapped to those of the LADM. The associated LADM geometry has also been included. As may be seen from the table, the IFC has more semantics than the LADM. This means that many of the entities, such as *IfcSpatialStructureElement*, cannot be matched explicitly.

Of particular interest are *IfcOpenShell* and *IfcZone.* An *IfcOpenShell* combined with *IfcFacetedBRep* boundary representation, can be used topologically to include open volumes. An example of this is given in the first use case. *IfcZone*, allows complex spatial units to be grouped, even if they are not adjacent to one another. For example, an apartment spread over several floors and with different shaped spaces or an organisation which owns parts of two existing buildings, such as the Autodesk headquarters illustrated in Figure 9.

Noticeably, in contrast to research reported earlier, the half space solid has not been included in the model below or in the semantics. This is due to the fact that in practise the IFC files generated by the use cases did not include it. A space modelled as an open or closed shell with boundary representation was enough. This does not exclude it being used, however, in the future. In this case a *IfcPolygonalBoundedHalfSpace* could prove useful as well. The IFC is large enough to provide multiple interpretations.

4.6. Mapping the LADM to the IFC

Figure 28 models what IFC entities are required in order to obtain the information most relevant for a Map of Legal Spaces in STEP's Express-G notation. This model view definition has been made with reference to the LADM. While the previous example, Figure 15 illustrated one entity using Express-G notation, Figure 28 puts it in context. In further contrast to Figure 15, it does not include the attributes of every entity, but provides an overview.

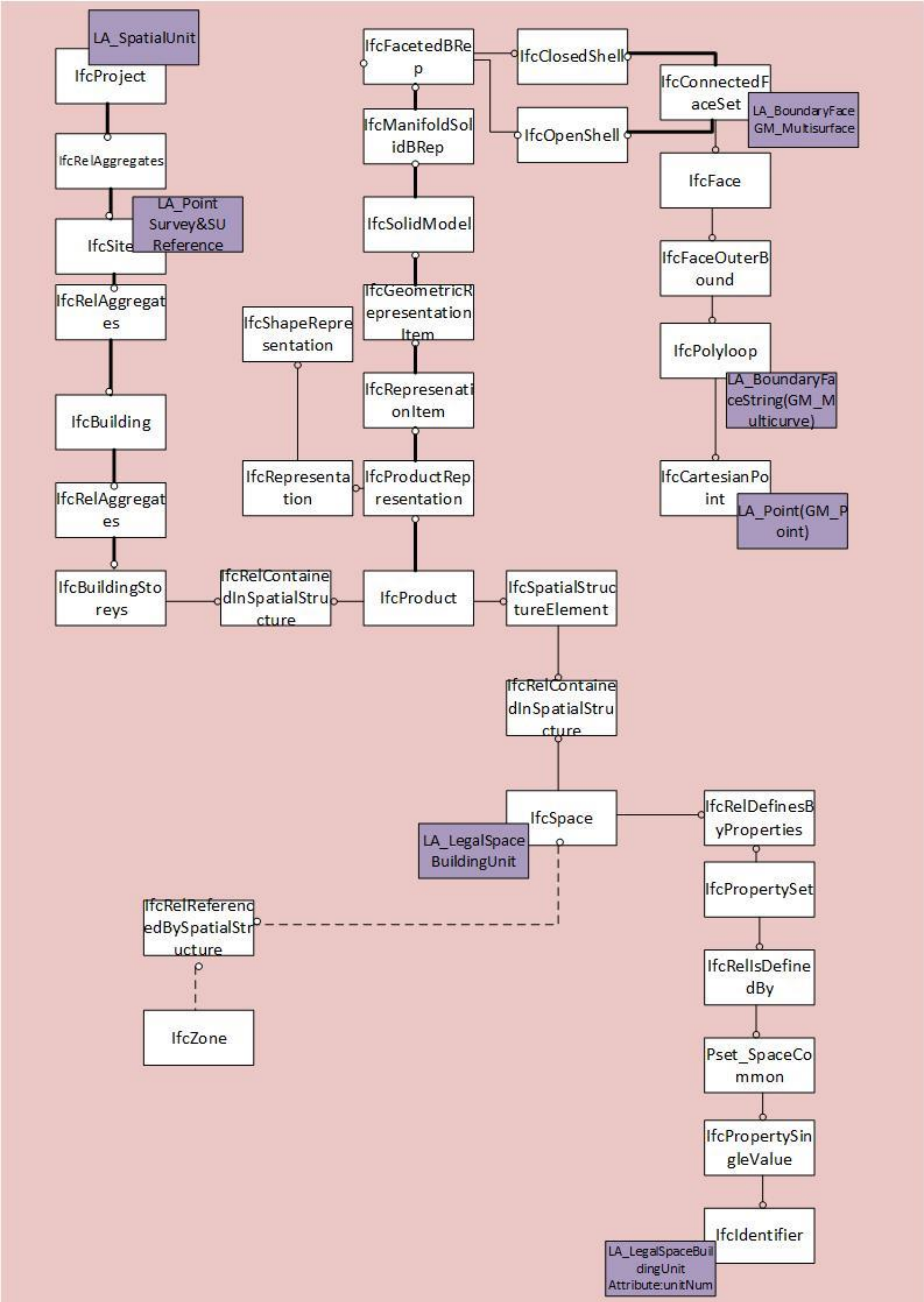


Figure 28 Mapping the IFC to accommodate the LADM modelled in Express-G

4.7. Mapping the IFC to the LADM: Model View Definition

While Figure 28 includes the main entities required for the LADM and many of the connections between them, it is a simplification and not a full Model View Definition. The IFC model is a highly complex one, currently with more than 800 entities. It is not only the entities themselves which make it complicated, but also the fact that they can be connected up in different ways. This means that the same result can be achieved in different ways and that it can be modelled in different ways. Ultimately, it is the Express code which best documents it.

In order to cope with this, a tool has been created. This is the Ifc Doc tool or Ifc Documentation Generator, which can be downloaded from the buildingSMART website. This software helps create a complete Model View Definition which can then be communicated electronically in XML.

Figure 29 shows a part of a complete Model View Definition for a 3D Cadastre. The 3D Cadastre *.ifcdoc* baseline file is listed on the left (circled in black) The red box on the right graphically illustrates some of the additional entities required for the 3D Model View Definition which are not included in Figure 28. Abstract entities are modelled in grey and the rest in black. Thus it can be seen, for example, that while a space can be connected up into a zone, a zone itself needs to be part of an *IfcGroup* and an *IfcSystem*

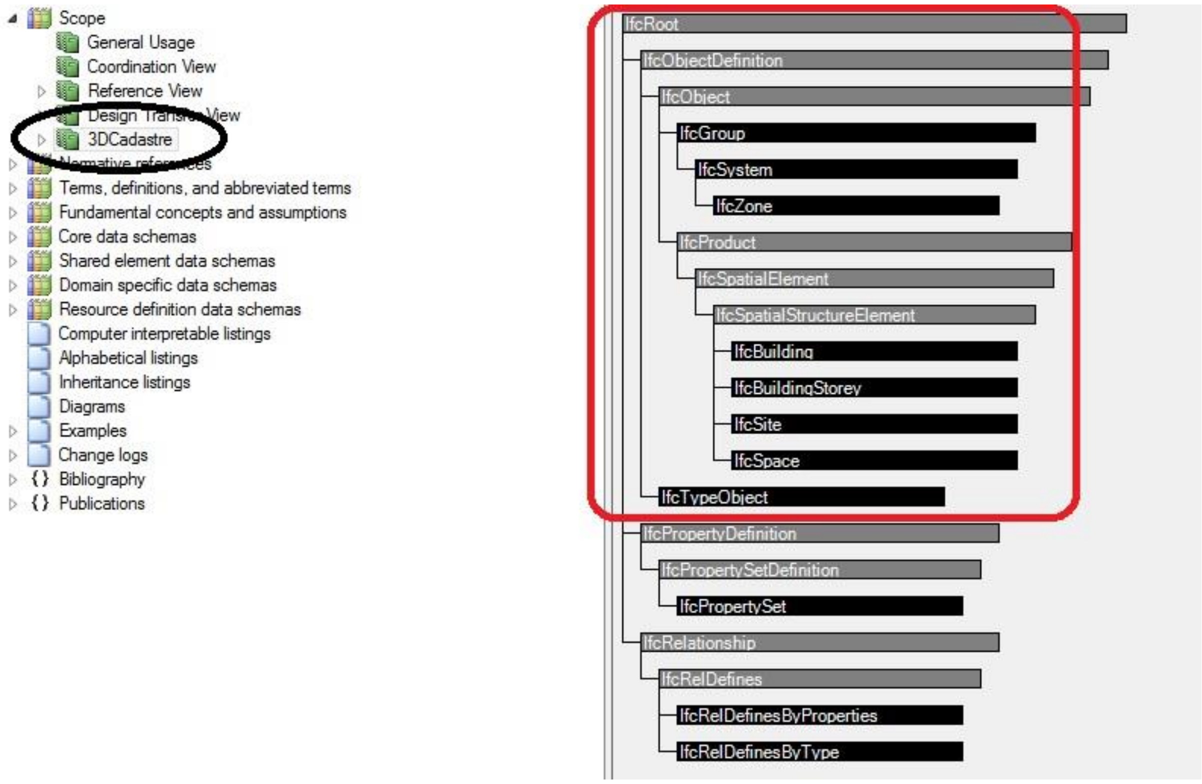


Figure 29 3DCadastre Model View Definition

4.8. Mapping the IFC to the LADM: Geographic Co ordinates

Every BIM requires the *IfcProject* entity, of which there is only ever one in an exchange context. *IfcProject* is the entity from which all other entities stem. Below it, *IfcSite* has been matched to *Survey::LA_Point* and to *LA_SpatialUnit referencePoint*. This is due the fact that geographic points are given as an attribute to I*fcSite* once in a BIM. As is illustrated in the code snippet above, from then on they are given as Cartesian points which leverage off these geographic points. Figure 30 shows *IfcSite*'s attributes.

```
ENTITY IfcSite
  SUBTYPE OF (IfcSpatialStructureElement);
    RefLatitude          : OPTIONAL IfcCompoundPlaneAngleMeasure;
    RefLongitude         : OPTIONAL IfcCompoundPlaneAngleMeasure;
    RefElevation         : OPTIONAL IfcLengthMeasure;
    LandTitleNumber      : OPTIONAL IfcLabel;
    SiteAddress          : OPTIONAL IfcPostalAddress;
END_ENTITY;
```

Figure 30 IfcSite showing optional attributes (buildingSmart-tech.org)

Only one set of geographic co ordinates are given in an IFC model. These can be used in two ways by the LADM. The first is to calculate more points in order to fulfil the survey point requirement. This could be done by converting the many Cartesian points in the file into geographic co ordinates. The second way in which the LADM uses co ordinates is to register one reference point for each spatial unit. The points provided by *IfcSite* could be used directly for this purpose, or converted if necessary.

4.9. Mapping the IFC to the LADM: the Site – Building - Storey Hierarchy

The model begins with *IfcProject* and then decomposes into *IfcSite*, *IfcBuilding* and *IfcStorey*. While there can only be one *IfcProject* there can be multiple sites, buildings and storeys (ground floor, first floor etc) within a project. The *IfcSite*, *IfcBuilding*, *IfcBuildingStorey* hierarchy accommodates this. This parallels with the fact that a 3D cadastre may have to face a registration in which a parcel is spread over separate sites, buildings and storeys as well.

LA_SpatialUnit has been mapped at the level of *IfcProject* as it is also the class from which all other classes in the LADM Spatial Unit package stem. An LADM Spatial Unit can encompass a utility network, for example underground pipes but also the plumbing on a major building site. This can be in addition to an *LA_LegalSpaceBuildingUnit*, which is a specialisation of *LA_SpatialUnit*.

A spatial unit could, however, also be mapped to an *IfcProduct*. This would have made many of the entities in the diagram redundant. This has not been done so that geographic co ordinates at the *IfcSite* level can be accessed. While the building and building storey entities have been included in the mapping, *LA_LegalSpaceBuildingUnit* has been mapped to *IfcSpace*. This is in spite of the fact that both building and building storey are aggregating entities which allow a selection of buildings and storeys to be grouped into one.

This functionality is also available at the *IfcSpace* level, and in practice this is what has worked best. *IfcSpace* can be grouped into a zone, which allows for multiple buildings, appartments and other legal spaces to be grouped together into one project or spatial unit.

4.10. Mapping the IFC to the LADM: Zones and Spaces

IFC classes can also encompass virtual spaces (in addition to the physical spaces). While a physical space may be a room, a virtual space may be a collection of rooms grouped together for a specific purpose such as an energy analysis (Weise 2009). In turn spaces can be grouped together to form zones, such as one put together to assess the fire safety of a building. While the spaces within a zone are generally positioned adjacent to one another, they do not have to be (Liebich 2009). A legal space is quite similar to such a virtual space, which can also encompass a number of volumes. Therefore, these spaces and zones are of particular interest in the context of a 3D Cadastre.

Spaces and their boundaries can be virtual objects used to calculate quantities for various forms of analysis related to spaces or rooms in buildings (Weise 2009). An example of this is Quantity take off for Cost Estimating, where the cost of the building is estimated at an early stage of its design and Facility Management Work Package Estimating where areas are estimated with regards to maintenance projects such as freshening up paintwork and cleaning walls. These analyses are defined using a Model View Definition. If these space objects were included in a 3d Cadastre, similar analyses could be completed. The value of a legal space, for example, could be calculated from the cost of a square metre of living space in a particular location. If a building was renovated, or if an apartment building was subdivided in a different way, the size of the new legal space could be calculated from the model alone.

4.11. Mapping the IFC to the LADM: Geometry

Figure 20 illustrates a key difference between the IFC and CityGML which, in turn, is also a key difference between the IFC and the LADM. The IFC works primarily with solids rather than boundary representation. Thus in the IFC a wall is a wall, an extruded solid entity. In CityGML a wall is a collection of surfaces built up from linear rings joined to create polygons.

There are many types of solids in the IFC, as befits a model of more than 800 entities. In general, these solids are made by extruding from a circle, rectangle or polygon. An example of how this works is given through the definition of half-space solids. As illustrated in Figure 31 these solids are formed when Euclidean space is divided into two convex sets by a hyperplane. The hyperplane (*IfcPlane*) is illustrated by the red square in Figure 31. A

Boolean operand decides on which side the solid will be extruded, in this case upwards without boundary.

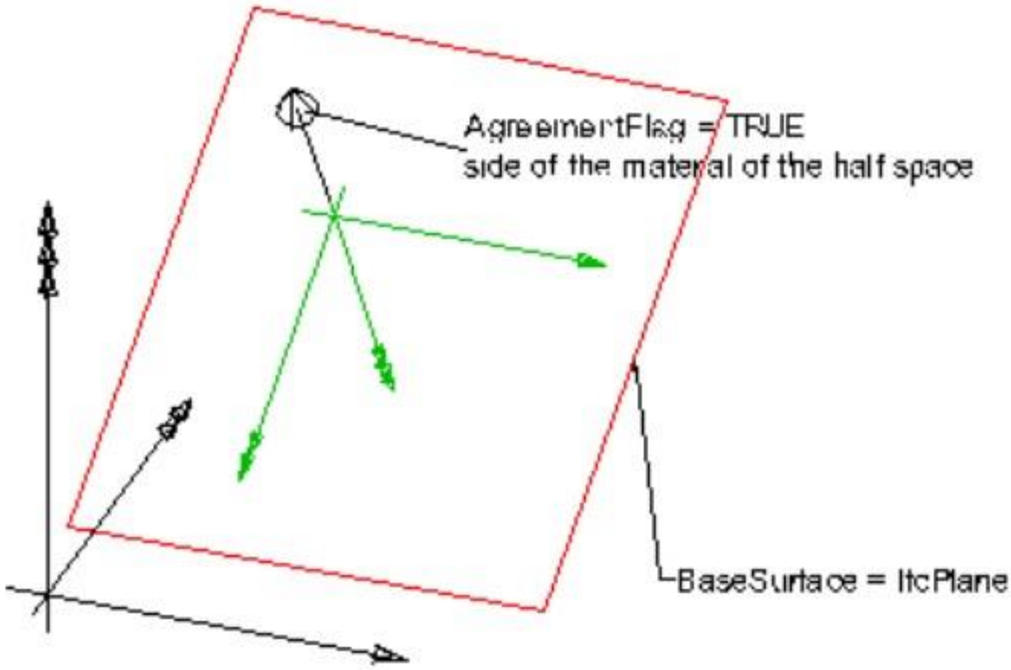


Figure 31 Half Space Solids (buildingsmart-tech.org)

A second half space solid, illustrated in Figure 32 also has a hyperplane (illustrated in blue). This time, however, the agreement flag is false. In this instance the extruded volume is capped. The words ‘local placement’ refer to Euclidean space which is defined in the IFC by Cartesian points.

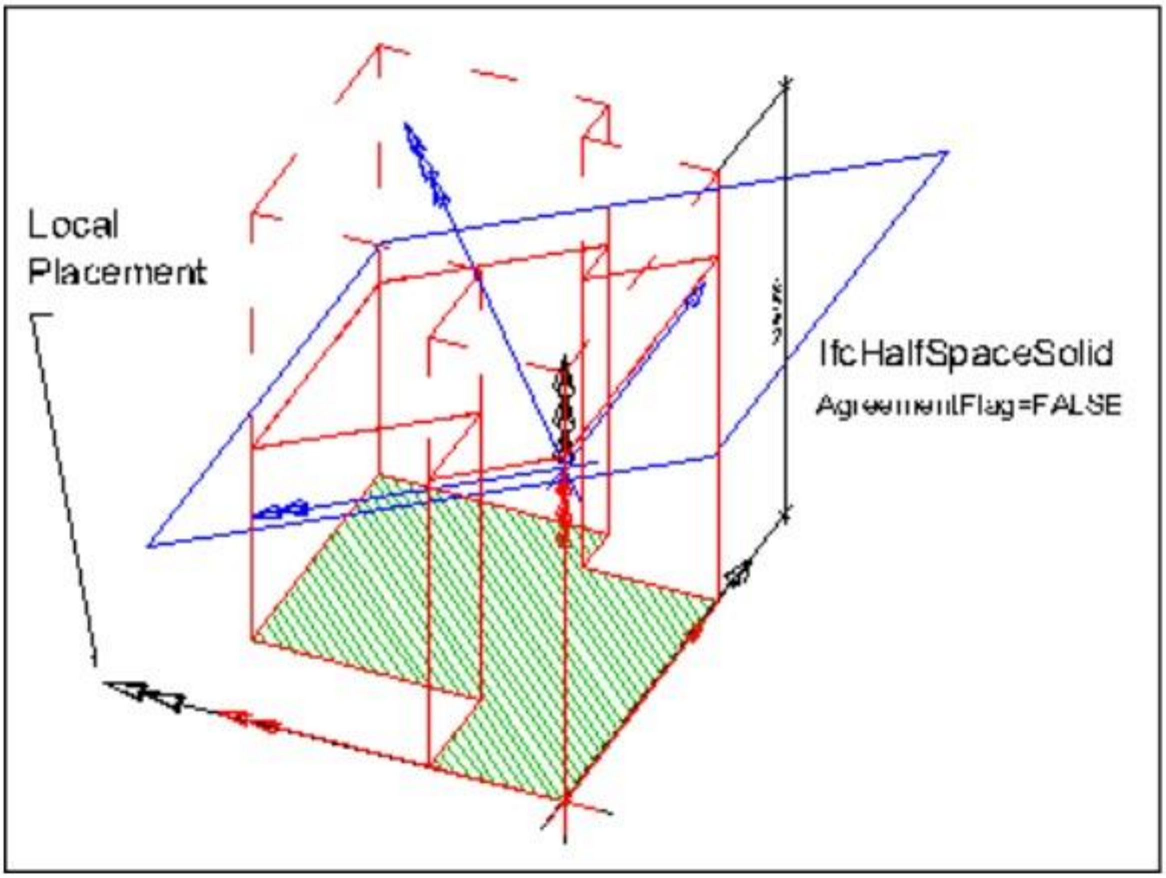


Figure 32 IfcHalfSpaceSolid (buildingsmart-tech.org)

In spite of the fact that the IFC works primarily from solids, it also allows many types of boundary representation. While the obvious place to look for these many types is in *IfcTopologyResource*, *IfcGeometricResource* can also provide options. Both *IfcTopologyResource* and *IfcGeometricResource* can be found in the resource layer of the simplified concept model illustrated in Figure 14) .

One of the key requirements defined in Table 8 is that the 3D Cadastre be topological. A further constraint is that land administration databases generally work with simple geometry. This is illustrated by the geometry of the Dutch *Kadaster*'s database (http://brk.kadaster.nl). This database works with polyloops (*lijnketens*). Although it officially works with curves between the nodes which make up the polyloops in reality planar curves work best (Quak 2017). It is a topological database, which uses one '*kaartlijn*' to define the boundary between spatial units.

Three forms of geometric boundary representation have been chosen from the many options provided by the IFC. The basic building blocks of all of them are points (nodes), edges (lines) and surfaces (faces). None of them involve curves, unless it is planar. They are open shell, closed shell and faceted BRep.

An open shell is a collection of surfaces. It is topological entity but is not a closed topological entity. Figure 38 illustrates an open shell, written out in the *.ifc* exchange format.

```
#239= IFCDIRECTION((1.,0.,0.));
#241= IFCDIRECTION((0.,0.,1.));
#243= IFCCARTESIANPOINT((-4518.52645503,4025.19280596,1000.));
#245= IFCAXIS2PLACEMENT3D(#243,#241,#239);
#246= IFCLOCALPLACEMENT(#96,#245);
#247= IFCCARTESIANPOINT((0.,0.,0.));
#249= IFCCARTESIANPOINT((3716.17430086,0.,0.));
#251= IFCCARTESIANPOINT((3716.17430086,-9180.69121816,0.));
#253= IFCCARTESIANPOINT((0.,-9180.69121816,0.));
#255= IFCPOLYLOOP((#247,#249,#251,#253));
#257= IFCFACEOUTERBOUND(#255,.T.);
#258= IFCFACE((#257));
#260= IFCOPENSHELL((#258));
```

Figure 33 IFCOpenShell in code

Entities #239 to #246 define where the open shell should be positioned. This is achieved through the medium of Euclidian space, and Cartesian points #247 – #253 are positioned within that space. The points, or nodes are connected up into a polyloop (#255) which then becomes an *IfcFaceOuterBound* and then an *IfcOpenShell*

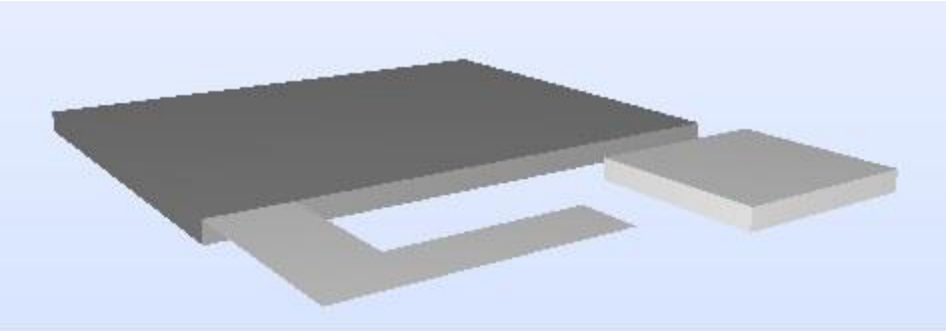


Figure 34 Zone of open and closed open shells. The open shell (at the front) is made up of a single face in this case

A closed shell is a space enclosed in a collection of connected faces or surfaces. Whereas an open shell has one or more sides missing, thus leaving it open, a closed shell does not. Both the open and closed shell can be represented by a faceted brep. This simple form of boundary representation has planar faces and straight edges. Its edges and vertices are sourced implicitly from the polyloop entity rather than being restated.

Open and Closed Shells and faceted brep can be mapped easily to the LADM. The Cartesian points which are their most basic building block maps to *LA_Point (GM_Point)*, the polyloops formed from the points equate with *LA_BoundaryFaceString (GM_Multicurve)* and the connected faces which edge them (*IfcConnectedFaceSet*
) to *LA_BoundaryFace(GM_Multisurface*). When all of these building blocks are put together they form the Open and Closed Shells with faceted brep which represent *IfcSpace*.

While this thesis has chosen to concentrate on open and closed shells geometrically represented with faceted Breps, there are more ways to topologically enclose *IfcSpace*. One way, which was considered earlier during the research process, is that of Ifc thermal space boundaries. IFC thermal space boundaries are designed to be used by Heating Ventilation and Air Conditioning specialists in order to calculate how much energy a building consumes. They can be defined at different levels. A first level space boundary is simply a shell, with no references to spaces outside it. A second level space boundary, however, does reference objects around it and is thus topological (Liebich 2009). Figure 35 illustrates how this works. Whereas a first level space boundary only references the six surfaces of Space 005 (floor, ceiling and four walls), second level space boundaries add an extra surface by means of more connection geometry to reference the existence of the wall between Space 003 and Space 004.

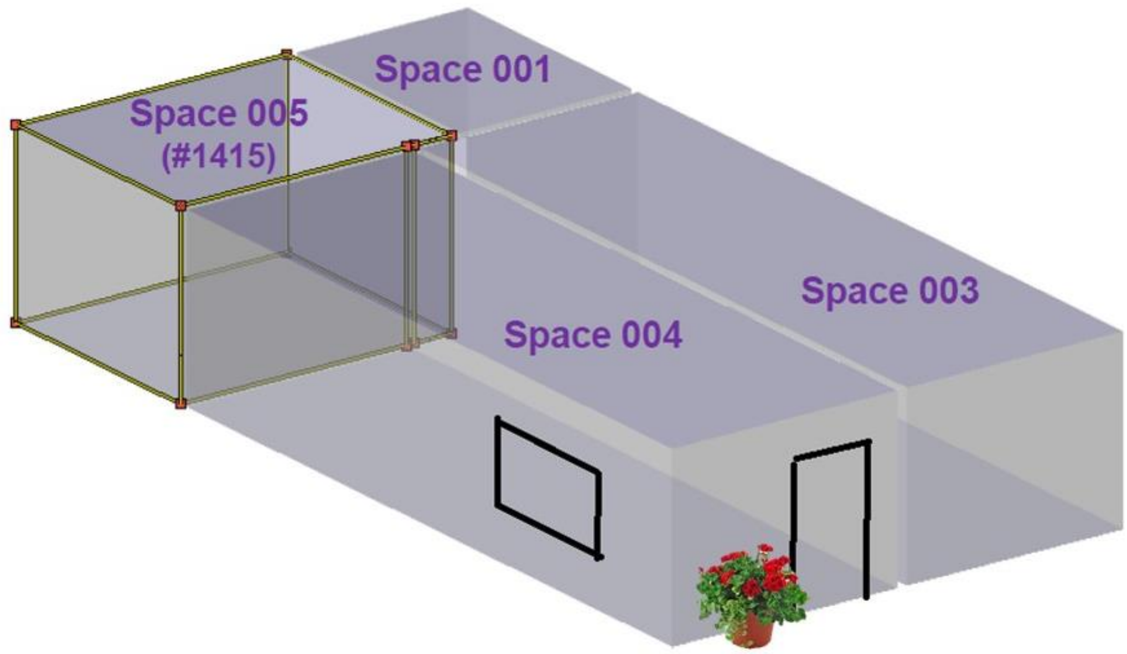


Figure 35 IFC topological 2nd level space boundaries (Weise 2009) with additions by author

A problem associated with the use of thermal space boundaries is that the topological boundaries run between separate spaces. While the spaces are bounded by the inner edge of the walls of a room, the 2nd level space boundaries are positioned within the wall itself at its median point. In many regional cadastral models the median of a shared wall is taken as the boundary between two spaces. This means that this capability could have some applications.

A further option would be to use a buffer, something common in the GIS world. Although a buffer or offset as it is known in the BIM world could be used, this process would be complicated and require the use of a Feature Manipulation Engine (FME) which would in turn mean the loss of IFC semantics (Krijnen 2017). What clinches the argument, however, is the fact that there is no need to work with the space boundary option as the IFC provides plenty of other ways to represent spaces topologically.

4.12. Mapping the IFC to the LADM: Property Sets

The buildingSMART website describes property sets as ‘a way to exchange alphanumeric information attached to spaces, building elements and other components’. Property sets are a way to extend the IFC model without changing it at a class level. The property sets work as a container class so that instances can be added. This can work within the framework of the common or predefined property sets (*p_set*) which are included from IFC2*3 onwards.

IfcSpace, for example, has a number of predefined properties (*Pset_SpaceCommon*). One of these predefined properties, an *IfcPropertySingleValue* could be used in conjunction with *IfcIdentifier* to provide a reference ID for each spatial unit. This example has been used in the mapping illustrated in Figure 28. In this instance, *IfcIdentifier* from *Pset_SpaceCommon* has been mapped to an attribute of *LA_LegalSpaceBuildingUnit*, *unitNum*.

Property sets have been included in the IFC model so that attribute definitions from different disciplines can be internationally standardized at a basic level. The use of *Pset_SpaceCommon* to provide an Identifier is an example of this. Just as the LADM itself can be extended and adapted for regional or national use, so can the IFC. These IFC basic property sets can then be complemented by regional property sets, or property sets agreed upon in projects.

A further example of a datatype which could be useful to the LADM, is that of *IfcLabe*l, illustrated in Figure 36. This could be mapped to the type attribute of the *LA_LegalSpaceBuildingUnit* to illustrate whether the unit be shared or individual. An apartment would be an individual unit and common areas within the building, for example the foyer, could be denoted as shared (Lemmen 2010).

Name	**Property Type**	**Data Type**	**Definition**
Reference	IfcPropertySingleValue	IfcIdentifier	An identifier is an alphanumeric string which allows an individual thing to be identified. It may not provide natural-language meaning Reference ID for this specified type in this project (e.g. type 'A-1') (www.buildingsmart-tech.org)
Category	IfcPropertySingleValue	IfcLabel	Category of space usage or utilization of the area. It is defined according to the presiding national building code.

Figure 36 Authored property set as addition to Ifc for use by a 3D Cadastral database (based on property set use definition IfcSlab)

5. Legal Framework

Chapter 4 looked at what data needs to be obtained from the IFC in order to correlate it with the LADM. Chapter 5 looks at a workflow which could be instigated in order to obtain this data. While Chapter 4 is based on the IFC and includes an MVD, Chapter 5 uses the IDM for inspiration. The chapter culminates with a workflow modelled in the IDM's business process modelling notation to detail what and when needs to be acquired.

5.1. How the BIM data for legal spaces could be obtained:The Environs Act

At this point, the Netherlands is still working on a 3D Map of Legal spaces. Within the same organization – the *Kadaster* -, however, moves are afoot to revamp the Large Scale Topographical Map (*Basisregistratie Grootschalige Topografie - BGT*) of the Netherlands. This map is a digital map which illustrates buildings, roads, water, railway lines and vegetation simply and clearly. It is the result of the cooperative efforts of the municipalities, provinces, water companies, the Ministry of Industry and Trade (*Economische Zaken -EZ*), the Ministry of Defence, the organization which administers the railways (*Prorail*) and the organisation which administers infrastructure (*Rijkswaterstaat*). Each member of the group is responsible for a section of the digital map (kadaster.nl/bgt).

The revamp of the Large-Scale Topographical Map (*BGT*) is being completed within the legal framework of a revolutionary law, the *Omgevingswet* or 'Environs Act'. This act is replacing tens of other laws and hundreds of regulations (see Figure 37) with the aim of simplifying the system and making it more user friendly. Concurrently, the management and development of water, air, soil, the natural environment, infrastructure, buildings and cultural heritage will be able to be done more efficiently and effectively.

Figure 37 Why we are introducing the Environs Law: There are so many rules and regulations that I can't see anything around me anymore! www.k2next.nl

A key part of this process is the incorporation of BIM files into the system. These will be obtained from building registrations submitted to the municipalities. The number of BIMs being created within the Netherlands is steadily increasing. At this point, buildings and other constructions such as infrastructure which cost €10 000 000 and above are being designed using a BIM (Schapendonk 2016 Appendix 1). The adoption of BIM is a process which was stimulated rather than hindered by the recession which began in 2008 (Schapendonk 2016 Appendix 1). This is due to the fact that 10% of the costs of every building are lost due to things going wrong. Working from a BIM helps reduce these costs.

A further factor at play is that those purchasing a new building are choosing to have them come with a maintenance contract, for example, for fifteen years. This is because they believe that it results in a better quality building. This means that a BIM is maintained at the same time as the building. It has been decided that while the maintenance can be contracted out to a maintenance company, the BIM itself remains the property of the building owner or owners. This is to prevent the BIM having to be sold back to the property owner at an inflated price if the maintenance company goes bankrupt (Schapendonk 2016 Appendix 1).

A maintained BIM is of interest to a 3D Cadastre as it means that new 3D information can be collected and the registration updated when the building changes hands.

5.2. The Environs Act: *The Digital System*

An important component of the Environs Law is the Digital System (Digitaal Stelsel). This is divided into three parts:

- A user-centered portal which provides the information required for a permit or when filing a report to private individuals, businesses and governing bodies. This is done in a standardized format.
- A communally-defined, central information infrastructure which is based on digital standards
- Separate 'Information Houses' which are connected up to the information infrastructure. These meet the information needs of project initiators and governing bodies with regards to the regulations surrounding water, soil, air quality and noise pollution. The information provided is, once again, based on standards. (www.digitaleoverheid.nl).

5.3. The Environs Act: Information House: Buildings

The Dutch *Kadaster* is to take stewardship of the Information House: Buildings. One of the Information House's key roles is to deliver Information Products. These include;

- the 'handover dossier', a central registration system based on BIM of all the drawings, calculations and the results from the quality assurance process (ie tests and inspections)
- a database of building regulations
- permit-free constructions
- digitalisation help – a centralised service for digitalising existing records so that they become standardised BIM models

Something that distinguishes the Information House: Buildings from similar systems worldwide is the inclusion of not only buildings but cables and pipelines; infrastructure including hydraulics, earth and roadworks; and railways.

5.4. More than a Smart City

We have long been told to 'work smarter, not harder' and the Environs Act is a perfect example of that. The Environs Act is a response to a nation's desire to do more with less, cut budgets and lighten the beauracratic load. A key premise of the Environs Act is to use information technology to 'work smarter'.

Modern Technology	Example from Environs Act– Information House: Buildings
Use of big data and analytics for deeper insights	BIMs (in the sense of 3D models) bring big data to the Dutch Cadastre and allow complex analyses to be made
Cloud for collaboration among disparate agencies	Interactive access to the 'Digital System' by users via a webservice. 3D BIM models also allow all parties (architects, engineers, safety experts and so on) involved to collaborate on the design and remains a central point for the integral management of the information throughout the lifecycle of the building project
Mobile to gather data and address problems directly at the source	Use of Crowd Sourcing to gather geographic data from the population at large via a website entitled 'Improve the Map' (www.verbeterdekaart.kadaster.nl)

Figure 38 Use of technology in the Environs Law: Information House Construction (aspects of modern technology taken from ibm.com)

Many of these principles are those of the Smart City movement, a term coined in 2008 by technology companies such as Cisco and IBM. Table 8 illustrates aspects which IBM's smart cities and the Environs Act have in common.

In contrast to this corporate, top down approach, the Environs Law places a central emphasis on open standards and bottom up. It is not intended to sell a product to consumers, but to help make sure that their tax euro is wisely spent. It is being created in response to the Dutch citizen's desire that the load of bureaucracy be lightened. Moreover, it is a democratic law intended to support new, sustainable developments within society and to represent the interests of all. (Pijpker et al 2015)

It has been noted that the world wide Smart City movement is currently paying little heed to 3D models, BIM and Geoinformation (Lathouwer 2016). In addition to this, there is very little use of standards. Rather, developments are being made in 'stovepipes' with little reference to each other. From another perspective the United Kingdom's influential newspaper *The Guardian* is urging the movement to 'support open-source collaborative technologies' so that it can 'generate a new vigour and vision' (Mason 2015). The Environs Act could be seen as a smart city or, in this case, smart nation solution which is endeavouring to do this.

5.5. Information House: Buildings *Capability*

Table 10 illustrates what the Information House: Buildings would like to be able to do with BIM files incorporated into the Large-Scale Topographical Map of the Netherlands.

Information House: Buildings	**Details**
Environmental Concerns	For example to illustrate the most appropriate place to put a swallow's nest on a building
Listed Building	To illustrate restrictions – for example it would be desirable if the BIM could be manipulated so that the different heritage paint colours allowed on a listed building could be visualised
Building Materials have to be included	To complete Noise Pollution analyses and energy analyses
Foundations have to be included	To see if foundation repairs have taken place in the past

Table 10 Information House: Buildings Capability

5.6. Modelling the Collaborative Process with IDM

One of BuildingSMART's open standards is the Information Delivery Manual. Perhaps the best way to explain part of this standard is to illustrate it using a proposed new workflow of the Information House: Construction. This workflow (see Figure 40 & Figure 41) which is intended to be used when obtaining a building permit, has been adapted to include procuring legal spaces for Land Registry as well. This has been completed in the Business Process Modelling Notation (BPMN) which is used by the standard. It should be noted that this process model is an interpretation made by the author for the purposes of this article rather than a document created by the Dutch Cadastre themselves. A further consideration is that these workflows would form a part of a far greater process model, with swim lanes for Advisors; Architects; Plumbing, Heating and Cooling Specialists and more.

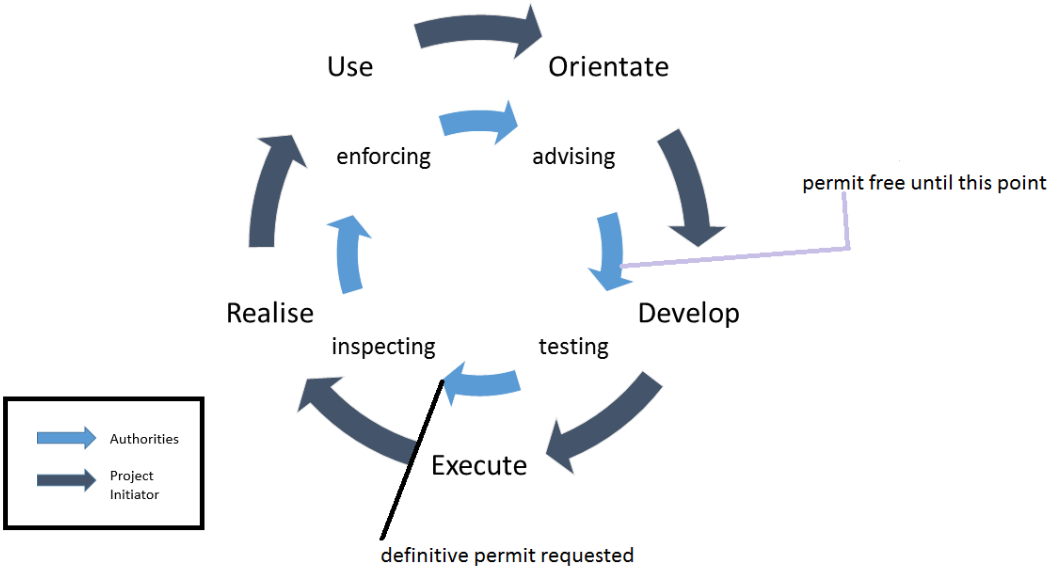


Figure 39Information House Buildings Obtaining a building permit workflow (tr. Pijpker 2016 et al)

A central goal of the presented research is obtaining 3D parcel data from BIMs already in existence. Key features would be selected from BIMs and recycled as legal spaces for input into a cadastral database. A collaborative workflow would further support the reuse of BIM data for 3D Cadastre purpose by improving the alignment of activities. Part of the process of gaining a building permit for a building would involve providing the Land Administration System with appropriate legal spaces. Figure 40 Figure 41 illustrate this process. In order to make the process as clear as possible, much of the text which would usually be referred to from the diagram itself using a number system has been left in the diagram.

Someone wanting to build or to renovate a house or other construction first seeks advice for example what can be built where and what cadastral and building regulations they should adhere to. They are also given access to a digital file of what has already taken place. They then set to work on a 3D BIM for the house. They design the construction to conform to cadastral and building regulations. Part of this process is to create a number of space objects grouped into a zone to represent the legal spaces in the building. The resulting 3D BIM is tested digitally to see if it conforms to the advice the Land Registry and the BGT gave in the original file. A definitive permit is requested and when it has been received the building is then constructed according to the design which has been submitted. During the building process things change, and the BIM which serves as the central point for the collaborative building process, with it. The ‘as built’ BIM becomes different to the BIM which was initially submitted to the authorities. The building is inspected and, where necessary, the building regulations are enforced. A further issue is that the building may be subdivided and put up for sale in a different manner than was initially communicated. Thus the cadastral data base needs to have an ‘as sold’ data set for its records. Underpinning the entire process is the use of open BIM standards which ensure that the data can be used by many, for a variety of purposes and for a long time.

This workflow has been given in the manner of a BIM open standard (the IDM) in order to illustrate how different actors should collaborate. Communicating it in this manner could also be helpful when detailing cadastral requirements to a building project. This workflow has been modelled on a similar workflow proposed in the Netherlands for obtaining BIM data for building registrations (Pijpker et al 2015). Figure 42 illustrates an Exchange Requirement template adapted for use in the workflow.

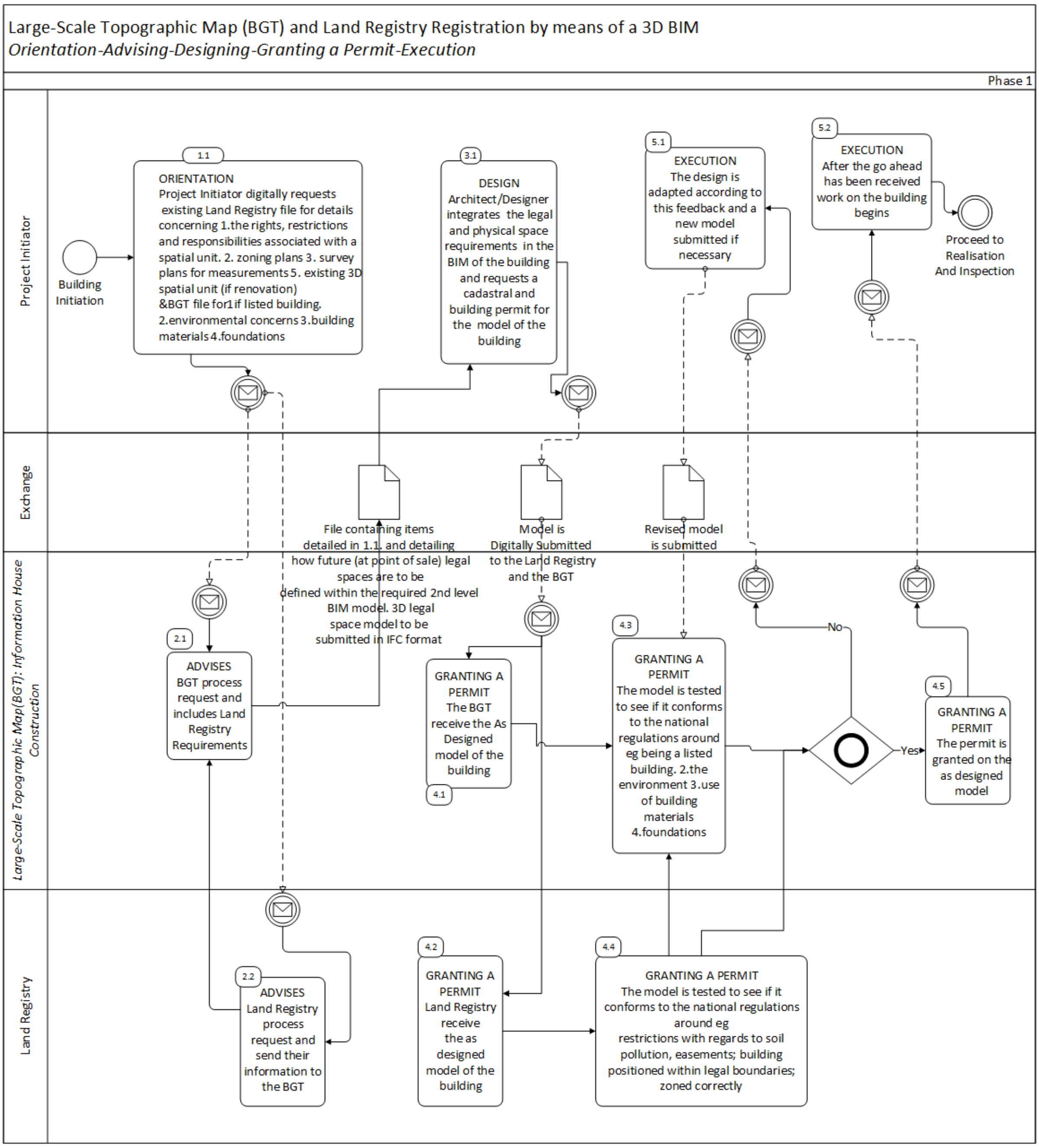


Figure 40 IDM's BPMN Workflow: Cadastral Registration by means of a 3D BIM Phase 1

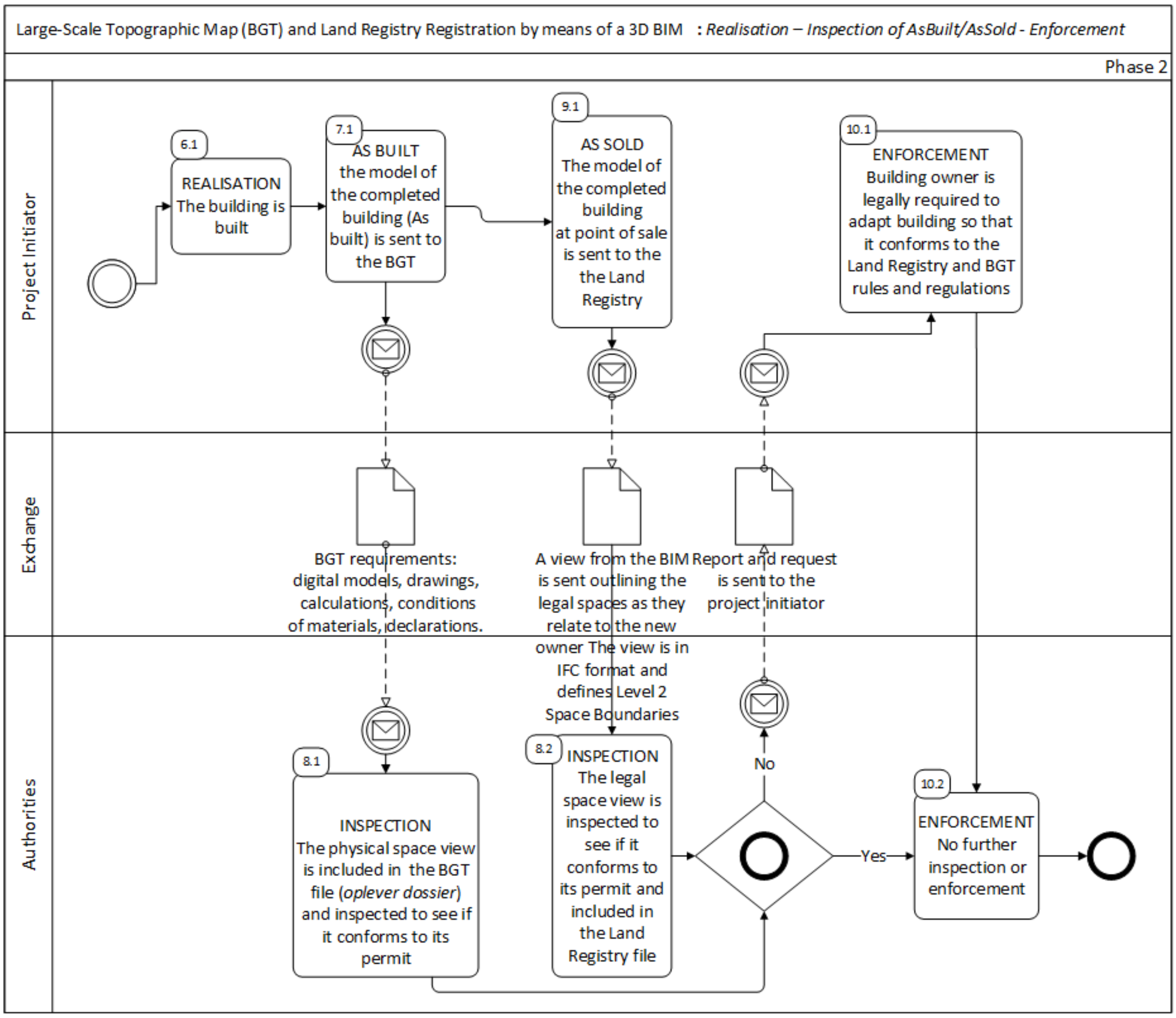


Figure 41 IDM's BPMN Workflow: Cadastral Registration by means of a 3D BIM Phase 2

Exchange Requirement

Name	**<Exchange Cadastre (Legal Space)>**

Identifier	<xxx>

Change Log		
<2016-06-29>	<Created>	<jo@cadastre.nl>

Project Stage	0	Portfolio requirements	
	1	Conception of need	✓
	2	Outline feasibility	
	3	Substantive feasibility	
	4	Outline conceptual design	
	5	Full conceptual design	
	6	Coordinated design and procurement	
	7	Production information	
	8	Construction	
	9	Operation and maintenance	
	10	Disposal	

Overview

Scope
<The scope of this exchange requirement is to enable the exchange of information related to 3D legal spaces which must be defined within BIM models before being lodged with the Cadastre>

General Description
< This exchange requirement allows for the provision of information at various stages during the design process including outline conceptual or sketch design, full conceptual design and coordinated design. The information provided at each stage is essentially the same.
However, the level of certainty regarding geometry required will increase at each stage allowing greater certainty in legal space definition.>

Information Description
<Information required concerning the definition of legal spaces includes:

- Common property
- Ownership spaces eg apartments>

Figure 42 Exchange Requirement sample adapted for the workflow

6. Use Cases

Chapter 6 looks at four different use cases. It begins with looking at how the IFC could be adapted to encompass 2D spatial units converted into topological volumes. Three further use cases look at the three scenarios outlined in Chapter 4.1. These use cases have been modelled to the requirements detailed in the workflow outlined in Chapter 5.6. As such they represent what is required at stage 3.1 (see Figure 40), the design stage rather than the as built design.

6.1. Use Case 1: Traditional Parcel Columns

The first use case is illustrated in Figure 43. A central principle of land registry systems around the world is that although a parcel of land or spatial unit is recorded in 2D, in reality it alludes to a 3D space. Unless there are other rights or restrictions recorded, this space reaches below the 2D representation to the earth’s core and endlessly up into the sky. This is shown in the first image on the left.

The central image is taken from a presentation given by Rod Thompson (2017). It illustrates how parcels recorded in 2D can be converted into 3D. A z axis is added to the nodes of each parcel, to represent what is illustrated in the first image.

The third image is that of an IFC Open Shell. This volume is made up of connected faces but has been left open at the top and bottom. While it is illustrated as an isolated case, it can be made topological and could be used to extend any 2D parcel into 3D.

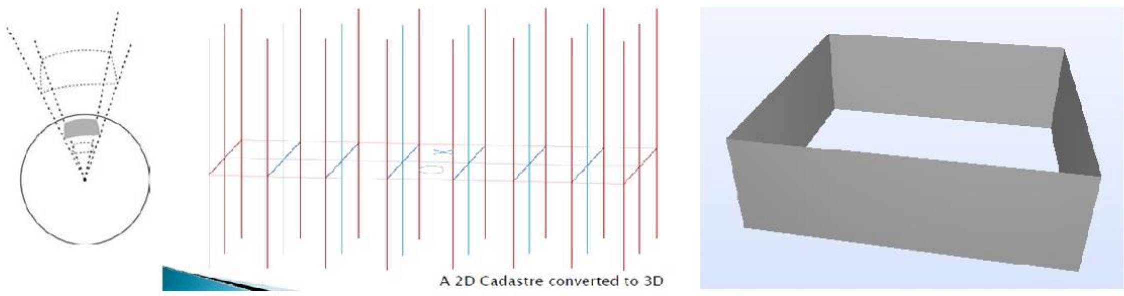


Figure 43 From left to right: from the earth's core up to infinity (Stoter 2004), the same concept in a topological database (Thompson 2016) and once again in an IFC topological Open Shell (author)

6.2. Use case 2 : Encroachment.

The first scenario defined in Chapter 4.1 is that of superficies. This is where the property of one party encroaches onto that of another. The encroachment of one body’s property onto that of another can take many forms. A common situation in the Netherlands is when the cellar of one house extends under the house of someone else. In another situation shown in Figure 25, a building is situated above a road belonging to the government. Figure 44 illustrates another form of encroachment. In this case, a building is larger than its footprint. This is not a problem if its bulk is contained within the parcel of land, as is most probably the case in the Evoluon in Eindhoven, but is a problem if the top of the building leans out over a land parcel belong to somebody else. As modern construction techniques allow these shapes, and modern taste for them is growing, this is a scenario with which a modern cadastre is more likely to be confronted with in the future.

Figure 44 From left: Design for a trapezoid -shaped building courtesy (Rogers Stirk Harbour + Partners (RSHP)Architechts)and two well-loved Dutch buildings - Nemo, Amsterdam and the Evoluon, Eindhoven

Figure 45 is a use case put together to demonstrate this scenario as being appropriate for 3D registration. It is illustrated with images stored in the .ifc data format. The fictitious building is illustrated in 3D on the left of Figure 45. The drawing on the right is of its registration in a 2D cadastre. The 2D drawing implies that the footprint of the building extends into two other parcels – 123 and 125. The reality, however, is different but difficult to understand without the 3D model.

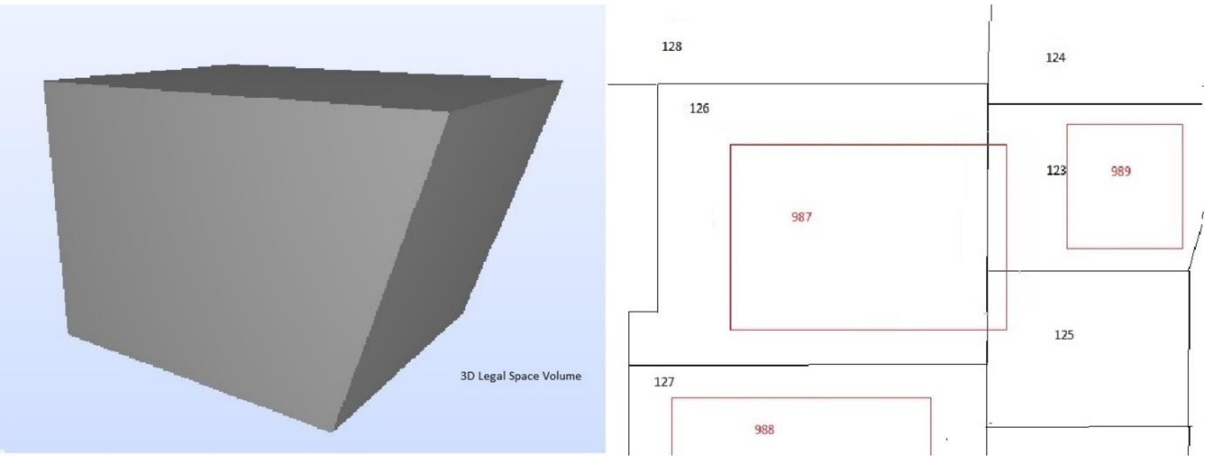


Figure 45 Use case Trapezoid building which leans out over the property of someone else, therefore illustrating superficies.

6.3. Use case 3: Lakeside Restaurant

This use case illustrates the second scenario outlined in Chapter 4.1. In this case there are multi-level use rights but in contrast to Use case 2, it involves more than one instance of superficies

The Lake Restaurant is a data set made available as an IFC file by the United Kingdom's National Building Specification. This specification is a case study project for the National BIM Library which is used to market the National BIM Library. This library contains proprietary and non-generic objects which are free to use and platform neutral so that they can be imported into BIM design projects (National Building Specification 2016). The data set is a complex design which is modelled down to the last detail. The data set is used within this paper to illustrate how legal spaces can best be taken from 3D BIMs. (National Building Specification 2016)

6.4. The Lakeside Restaurant in a 2D Cadastre

Buildings built above water pose a particular problem to a 2D Land Administration System. Imagine a situation where a privately owned parcel is situated above water belonging to the city council (government). Only the stilts that the building is built on make contact with the ground. Figure 46 illustrates how it could be registered. This method was used for a similar building in Amsterdam which was positioned above an underground carpark (Stoter et al 2012).

The round circles in Figure 46 represent 39 separate spatial units or parcels. There are a number of problems with this solution. The first is that on the basis of these records someone studying the records can only guess at what the building (**Error! Reference source not ound.**) looks like. The second lies in the maintenance of the records. Each one includes the rights, responsibilities and restrictions associated with the whole building. Not only would updating them all be prone to error but one could easily be inadvertently skipped while transferring the deed.

This manner of registration, which typifies the second scenario outlined in Chapter 4.1, makes the Lakeside Restaurant a perfect candidate for 3D registration.

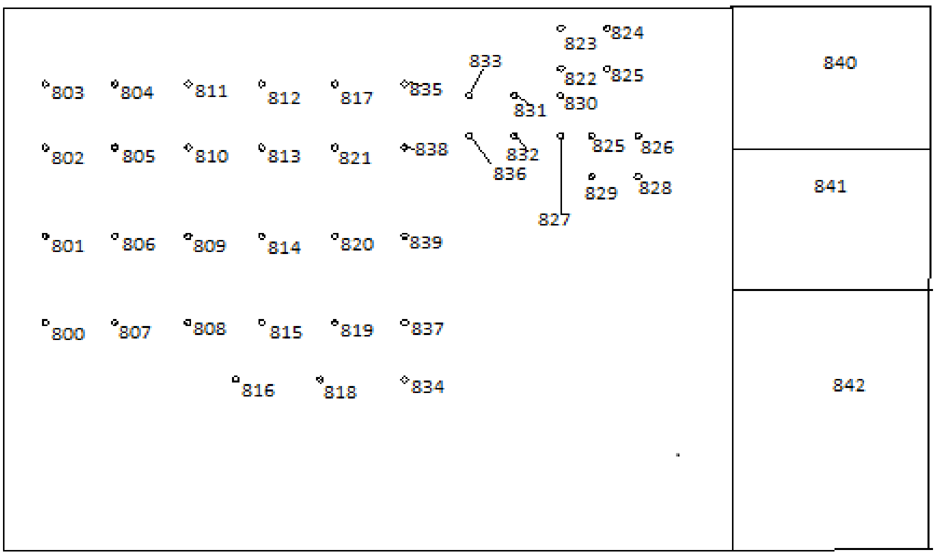


Figure 46 A construction built above water registered in a 2D Land Administration System. A separate spatial unit has been created for every pile foundation in the water.

Figure 47 the Lakeside Restaurant thenbs.com

6.5. The Lakeside Restaurant in a 3D Cadastre

An alternate method of registering the Lakeside Restaurant would be to do so in a 3D format. The data could be extracted from a 3D IFC model for use by a 3D Cadastre. The Lakeside Restaurant would be a particularly interesting space to register. To begin with, it is positioned above water. Not only is it positioned above property belonging to someone else but the boundary between the two properties is what could be described as an ‘ambulatory natural boundary’ (Thompson 2015). This means that the water levels beneath the building are not fixed, but rise and fall depending on the weather.

A further issue is that not only does the building encompass an open air (no top) outdoor deck, positioned above the water but that a number of other spaces within the building are not fully enclosed. One such space can be seen on the left in **Error! Reference source not ound.** where an outdoor eating area is shielded by a roof and partially covered walls. The closed part of the Lakeside Restaurant can be mapped to an *IfcSpace* object. This space object could be composed of a closed shell thus making it a topological volume. Figure 48 illustrates such a closed shell. In it, the restaurant has been revisualised as a volume. The terrace has also been reformed, to illustrate that it is a limited space both below and above.

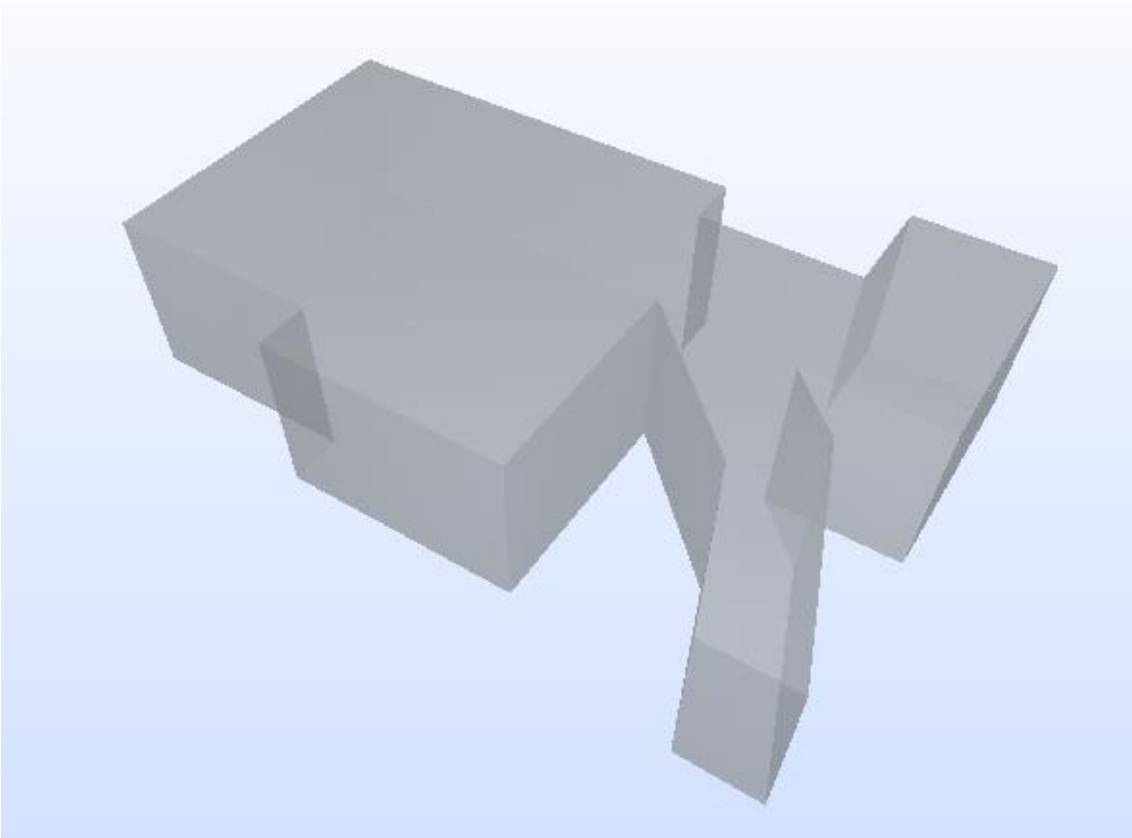


Figure 48 Conceptual Mass as IfcSpace object

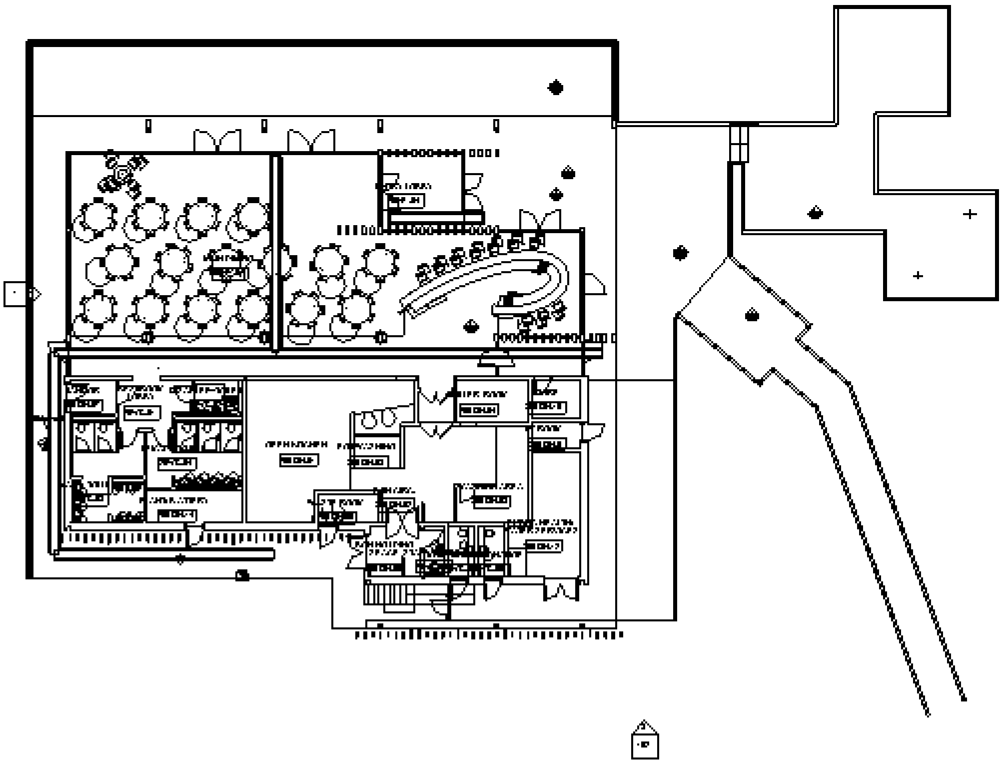


Figure 49 Floor plan of the Lake Restaurant

6.6. Use case: Apartment Block with Adjacent Underground Garages

A fourth use case looks at how useful a 3D Cadastre would be for apartment buildings and is based on the third scenario outlined in Chapter 4.1. Cross sections and floor plans for apartment buildings are already part of the Dutch *Kadaster*'s registration process. These, however, are less helpful when separate apartments have a different shape or a separate parking area. In this use case the apartments are the same shape but have separate underground garages positioned under the land of someone else.

The fourth use case is illustrated in Figure 50. The cross section and birds eye view drawings required by the Dutch *Kadaster* have been included, in addition to two further drawings. The first (top left) gives a 3D image of the apartment block. The second (top right) gives a cross section which shows that the garages are underground. The extract from the 2D map of legal spaces clearly illustrates that the garages are not only separate from the apartment block but are positioned under an adjacent parcel or spatial unit and thus illustrate superficies as well. The bottom right image shows the full extent of Apartment 1 – the living space and the garage.

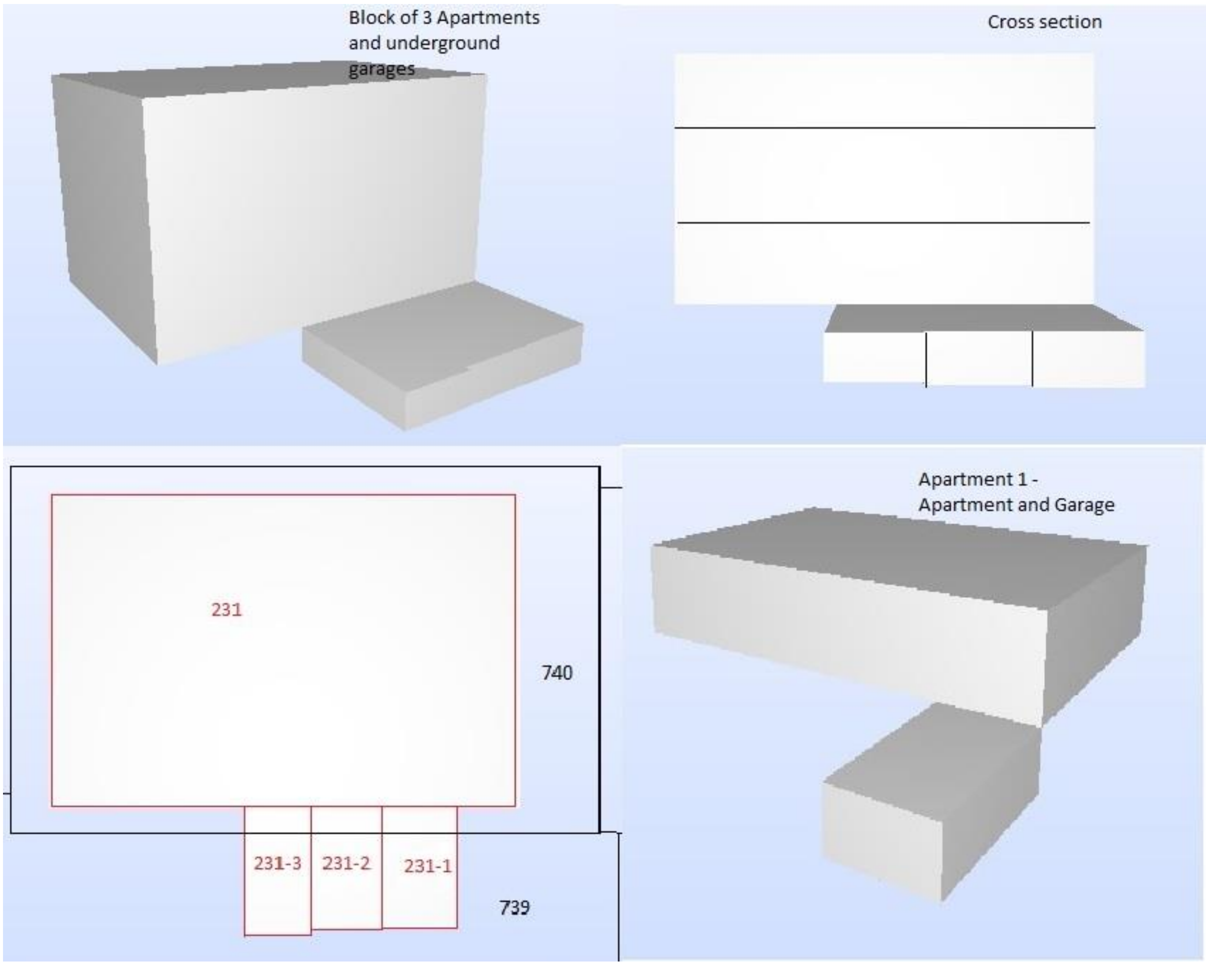


Figure 50 Use Case 4 Apartment Building with separate garages

How the images have been grouped together is based on what was determined as relevant for a 3D Cadastre by Stoter, van Oosterom and Ploeger 2012. While the images from the 2012 article were made in a Computer Aided Design (CAD) system and did not provide topological data, those in Figure 50 do. This means that the data can be validated and combined into an overview.

The living space and separate garage illustrated in Figure 50 could also be illustrated as follows (Figure 51). Although this manner is adequate for a small block of apartments, for a large one it could be useful to have both types of visualisation.

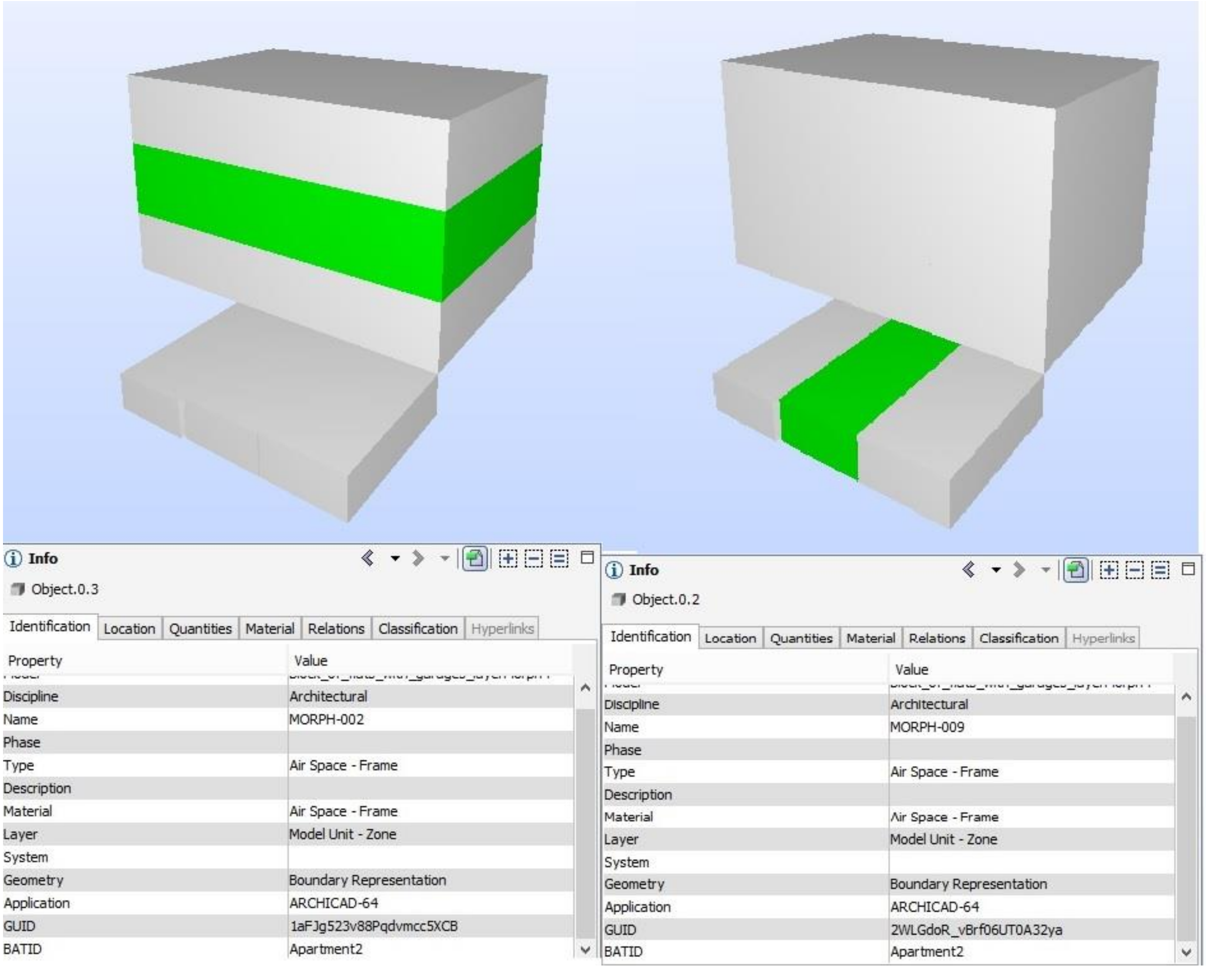


Figure 51 Apartment 2 highlighted in context

Use case 4, as were use case 1 and 2, was made in Archicad, exported as an IFC file and then illustrated in the Solibri Model Viewer. While including administrative information in an Archicad file is a simple matter, care needs to be taken that it is also exported to IFC. The two tables of info in Figure 51 show what has been exported into the IFC, which in turn parallels with what is illustrated in the data model mapping the IFC to the LADM in Figure 28.

To begin with, the two info tables show that the apartment and garage are two separate objects of the type *IfcSpace* (Air Space – Frame). They are Object 0.3 and Object 0.2 and have separate unique identifiers or *IfcRoot* GUIDs. They are however, grouped into an *IfcZone* (Layer Model Unit – Zone) and have the same BATID. This second identifier was entered as *IfcIdentifier* under *Pset_SpaceCommon* in Archicad. The geometry is given as boundary representation. This sums up the fact that a mass of Cartesian points have been joined to form topological surfaces which bind the spaces.

7. Analysis and Conclusion

7.1. Evaluation

This project began by putting together a research proposal. An important part of the research proposal were the research questions. This chapter will report on the answers to those questions, but will begin by outlining some of the challenges faced.

In order to answer the main research question, this thesis needed to bridge a number of divides. The first divide was between the educational programs at Delft Technical University, Eindhoven Technical University (Eindhoven TU) and of Science Geographic Management and Applications (GIMA) student.

The second divide was between the two technical universities involved. The fact that Eindhoven TU is not part of the GIMA meant that my Eindhoven supervisor was participating for the 'intellectual curiosity' and that officially I was not a student of his.

The third divide is between the worlds of GIS and BIM. These worlds have traditionally been separate and involve people from very different backgrounds. On the one hand there are geographers, on the other there are architects. The differences between the fields is further outlined in Table 1. Although these fields are in the process of merging, this is an ongoing process.

The fourth divide was that of two languages. I am a native speaker of English, and can read and speak Dutch fluently. This meant that I could read a key work – a text concerning the Information House: Buildings written in Dutch.

Yet a further divide was that between the department in the *Kadaster* which administers the Large-Scale Topographic Map in the Netherlands and the department that administers the Land Registry. The idea that these departments can work together to obtain the necessary information is a radical and potentially divisive one which would need to be approached sensitively.

Working with Open BIM Standards to Source Legal Spaces for a 3D Cadastre

1) *Based on research already completed in this area, what is the best way to conceptually map BIM data and ISO 19152 together in order to produce input suitable for the creation 3D Spatial Units?*
   a) *How do BIM, ISO 19152 and the requirements for a LADM- based 3D Cadastral model compare?*
   b) *How can BIM best be structured in order for it to be inoperable input for the 3D spatial input?*

The IFC is a huge model with more than 800 entities in total. This fact, and how it is structured means that there are a number of ways to do the same thing and plenty of possibilities for meeting the requirements of an LADM based 3D Cadastral Model. While others active in this field (Atazedah 2016) have proposed the use of space objects complete with annotations regarding rights restrictions and responsibilities, this thesis took a more topological approach.

As mentioned in the previous paragraph, the IFC offers a number of ways to do the same thing. The Express G diagrams throughout this thesis illustrate how BIM could best be structured to achieve this.

2) *Which use cases of combined BIM and Cadastral data optimally illustrate the challenges which twenty-first century Smart Cities will throw at a 3D Cadastre?*
   a) *What types of object registration occur at a Cadastre?*
   b) *Which properties can be more adequately registered by a 3D Cadastre?*
   c) *How can these 3D cadastral entities be obtained from BIM and then incorporated into the design of conversion/derivation function?*

The types of object registration which occur at a Cadastre is detailed in the Introduction and the Literature Review. The chapters about Legal Spaces – for example *Legal Spaces Right of Ownership* discuss which properties can be more adequately registered by a 3D Cadastre. In addition to this, Chapter 4.1 gives a list of the registrations most suitable for 3D cadastral registration. This list formed the basis for three of the use cases

The four use cases illustrate how 3D cadastral entities can be obtained from BIM. This was defined as a set of requirements or Model View Definition which is how the world of BIM frames a derivation function. This Model View Definition can be electronically communicated using .xml.

3) *What are the requirements for a conversion/derivation function from BIM to a Cadastral entity?*
   a) *What are the advantages and disadvantages of similar functions or function components (for example validation code) already in existence?*
   b) *How can they be incorporated into a new conversion/validation function?*
   c) *How do BIM Model objects and Cadastral Model objects compare?*
   d) *What points or features should be converted and/or derived?*

The path from generalising BIM to closed topological volumes is one which has often been explored within the world of CityGML. The requirements for Cadastral objects, however, are different. This is not least due to the fact, as illustrated in Use Case 3, that legal spaces can be different shapes to the building itself. A further factor is that while legal spaces need to be topological, they do not always need to be closed.

With this in mind a number of test cases which incorporated the requirements for a Cadastral Model View Definition were made using commercial BIM software and then exported in IFC format. The validation process occurred as part of the export process.

4) *How should a test or Database prototype and test conversion of the proposed solution best be generated?*

   The BIM software includes a database which allows analyses to be made. The proposed solution was made and stored within this environment, exported in IFC and then checked in the Solibri Model Viewer to see if it conformed to what was required.

Although a database was not made, the objects were purposefully made as simple as possible and had topological boundary representation. This was done so that they could be inserted into a GIS database.

5) *How can the first conversion/derivation function be improved?*
   a) *What are the criteria for assessing the conversion /derivation?*
   b) *What are the guidelines for improving the conversion/derivation function?*

This process occurred between the creation of Use Case 3, which was made first and Use Case 1, 2 and 4. Use Case 3 was made in Revit and the last three in Archicad. Archicad allows more IFC features to be explicitly defined and exported than Revit.

6) *How successful is the improved version of the conversion/derivation function?*

The use of different software was a big improvement. In spite of this, however, the ifc is an exchange format and does not define the software itself. The only way to truly define the objects exactly as defined in the mapping, would be to program them or to come up with new software. The question is whether this software would find wide acceptance in the industry and be worth the effort. This will be discussed in the discussion section and future work

7.2. Discussion: A topological map of legal spaces: workflow

The ultimate goal of this research project is a Dutch 3D Cadastre. Ideally this 3D Cadastre would include a topological map of legal spaces which would allow information concerning the rights, restrictions and responsibilities of spatial units to be queried. Unfortunately, there is as yet no legal framework for this map in the Netherlands. In the meantime, research is focussing on how to lay the groundwork for it.

In a recent paper (Stoter *et al* 2016) describes how a 3D interactive pdf illustrating the rights, restrictions and responsibilities of the new Delft station was registered at the Dutch *Kadaster*. As mentioned earlier, this 3D interactive pdf was, however, not part of a 3D topological map of legal spaces but an addition to the current 2D registration. Its ground-breaking registration took two years to be finalised (de Riet 2016) due to the fact that the registration was initially completed in 2D and then reworked to include 3D information (Stoter et al 2016). If the initial registration had been accompanied from the beginning by a 3D legal space, it would have been completed in a matter of weeks rather than years (de Riet 2016).

This means that being able to present a completed legal space from the beginning of the registration process at the Land Registry would enable a faster and, presumably, far more efficient process. Following the workflow proposed in this thesis (see Figure 40 and Figure 41) would mean that this could be done.

This thesis began life as an effort to program a conversion function for the automatic extraction of legal spaces from existing BIM files. A use case illustrates what sort of legal space might be desirable in this situation (see Figure 48). One scenario is that the required legal spaces could be automatically extracted from the as built BIM by such a conversion function before registration at the Land Registry takes place. This scenario would, it is hoped, improve on the amount of time it took to register the 3D legal spaces at the Dutch *Kadaster*. It is not, however, what the workflow that has been proposed suggests.

Part of the process of creating the 3D pdf's which accompany the new Delft station's registration was discussing who exactly owned what. There was a discussion about not only who owned but who would maintain the staircase which runs between floors in the station. Exactly what its legal boundaries as opposed to its physical boundaries were was also a topic of discussion. A further case involved the area above a revolving door which extended into the property of a different party. This is illustrated on the right of Figure 52. Once this had been agreed upon, the question arose about who owned the space above the revolving door?

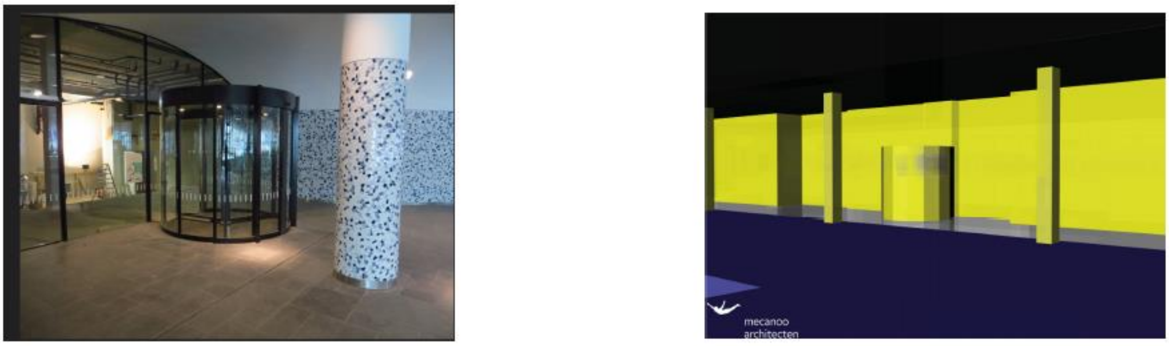


Figure 52 Who owns the space above the revolving door? Lesson learned from the Delft Station project (Stoter et al 2016)

One of the merits of defining the legal spaces in 3D early in the process rather than extracting them at the end would be that issues of rights, responsibilities and restrictions would arise during the building process and could be decided upon during that time. Communicating zoning plans, survey plan measurements and existing 3D spatial units if it is renovation at the beginning of the project could also prevent mistakes from being made. An easement through a property such as a public right of way, for example, could be taken into account in the design.

In conclusion, a workflow which meant that the process of defining and registering legal space in 3D ran concurrently to the design and building process itself would shorten the time it would take to register and be helpful in clarifying who owned what during the building process itself. It could also prevent infringements on the legal rights of others being made.

7.3. Discussion: A topological map of legal spaces: data

A BIM IFC file is semantically complex and relies largely on the use of solids formed in a different way to those found in GIS file. This makes the process of equating an IFC file with something recognisable to the GIS based LADM world a difficult one. While there is talk of including true solids into the geometric options provided by the LADM, at this point they are composed of boundary representation.

This thesis began by proposing to build a function to convert or derive legal spaces from existing data sets. Building such a function is an established form of research within the CityGML community which began with Nagel (2007) but which has been extended by others including Donkers (2015). As CityGML works from a foundation of GIS, there are parallels with what a 3D topological database would require. A key premise is to generalise, a concept taken from the world of cartography (Geiger, 2015).

Generalising existing files in an automated process is a neat and cost effective solution, and one which may in the end form some part of the workflow of obtaining IFC based legal spaces for inclusion in a 3D Cadastre. There are, however, a number of problems with this as a sole solution.

To begin with, there is rarely a central BIM file in IFC which is correct and without inconsistencies. This is due to the fact that a BIM file is created by a number of parties. For example Heating Ventilation and Air Conditioning specialists may form one file, Architects another. These files are created in the software of the specialist's choice, which may not always be the same. The IFC are the central storage and exchange format, but how the files are exported into IFC, the choice of which IFC class or representation depends on the software. For example, a simple extruded solid may be exported as an *IfcBuildingElementProxy* or as an *IfcSpace,* dependant on the software. When the merging process has finished, the parties involved often choose to overlay their original files with the new information rather than work from the central file.

One avenue which was explored in the quest to extract data from an existing *.ifc* file was to make use of heating zones already present in the model. These zones, when composed of virtual spaces, map well to the concept of the LADM's Legal Space Building Unit. Their existence in the IFC stems from the HVAC sector. Unfortunately, there were no heating zones defined in the file (see Figure 53).

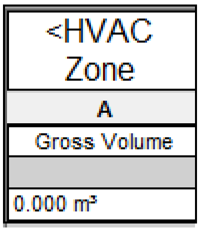


Figure 53 Illustration from Lakeside Restaurnt dataset which led to the conclusion that there are no zones (or spaces) to extract as no 'heating ventilation and airconditioning' zones have been defined.

These zones can also easily be defined in existing data models using software such as Revit and Archicad. They can then be selected and exported. The Air Space Frame annotation from Use Case 4 in Figure 51 refers to them. These thermal zones are made to fit within the walls of rooms, while the second level boundaries which bind them are placed at the median position between the inner wall surfaces.

In many land registry systems throughout the world, parcel boundaries - for example in apartment buildings - are measured to the median of the wall. Others, for example the Queensland government's building parcels (Stoter et al 2004), define spaces as being bound by floors, ceilings and walls. This capability, which is not illustrated with a use case, could be a potentially useful one to countries which work with a median boundary.

As mentioned earlier, a BIM file whether in Ifc or otherwise, is semantically complex and largely composed of extruded solids. This contrasts with the common use of boundary representation in GIS systems. Happily, the Ifc also offer a wide range of boundary range representations, which can also be topological. One of these, which is illustrated in Figure 54 is *IFCFacetedBRep.*

```
#401= IFCPOLYLOOP((#382,#375,#373,#389));
#403= IFCFACEOUTERBOUND(#401,.T.);
#404= IFCFACE((#403));
#406= IFCCLOSEDSHELL((#371,#380,#387,#394,#399,#404));
#408= IFCFACETEDBREP(#406);
```

Figure 54 Code Snippet illustrating the use of IFCFacetedBRep

IFC Faceted B Rep could be used both represent and topologically connect legal space entities. These legal spaces could be obtained at the same time as other building registration details are obtained. The Land Registry System could come in contact with builders at the beginning of the design process and, through means of a Model View Definition prescribed in IFC, request that legal spaces be provided.

While initially simple volumes, as illustrated in the use cases, these could progressively become more complex while incorporating decisions about how a construction would be subdivided. This would mean that such discussions took place during the construction process, and not at the end of it. If necessary, the design of the building could be altered, something which could potentially prevent conflict.

Figure 28, a mapping of the LADM to the IFC, could form the basis for the Model View Definition which would be sent to building designers. This Model View Definition has been put together in a way which would mean that simple IFC models could be stored in a GIS database. Working with IFC, a national Dutch standard as well as an international standard, would mean that the files stored in the Land Registry database would remain useable in the long term.

A digital BIM model becomes and remains the property of the building owner, although managed by a maintenance company. Ideally as the building is maintained, the BIM would be updated. This would allow a new legal space volume to be sent to the Land Registry database when the building was sold, or if a permit was requested.

The mapping of the LADM to the IFC included a number of key entities including *IfcSite*, *IfcOpenShell* and *IfcClosedShell*. The first, *IfcSite*, provides the geographic co ordinates from which the whole project leverages. *IfcOpenShell* and *IfcClosedShell* allow something of great interest to a topological 3D Cadastre. As the name describes, an open shell can be left open while still connecting up 3D closed volumes around it. This would allow, for example, outdoor areas such as balconies to be modelled, or for an empty lot positioned between other buildings to be included in a topological network. A topological network can be validated and eliminates the potential overlap of spaces. It also allow queries to be done.

The addition of a Land Administration identifier is also included in the mapping of the LADM to the IFC. This was done through the use of the *IfcPropertySet* container class and is illustrated by the fourth use case, the block of apartments. In this use case the property set functionality was used to add an identifier – Apartment 1. It shows up as a BATUID in Figure 51. This class could be used to further adapt a Model View Definition to the requirements of legal spaces.

As mentioned earlier, however, the IFC allows plenty of opportunities for adaptation at the instance level without necessarily having to resort to the use of Property Sets. Figure 55 illustrates this. The optional attributes for *IfcSpace* include a name, a description, an object type and a long name. For example an office foyer could be labelled F1 (name), ground floor office foyer and reception area (description), shared space (object type) and Walkie Talkie Building (Long Name).

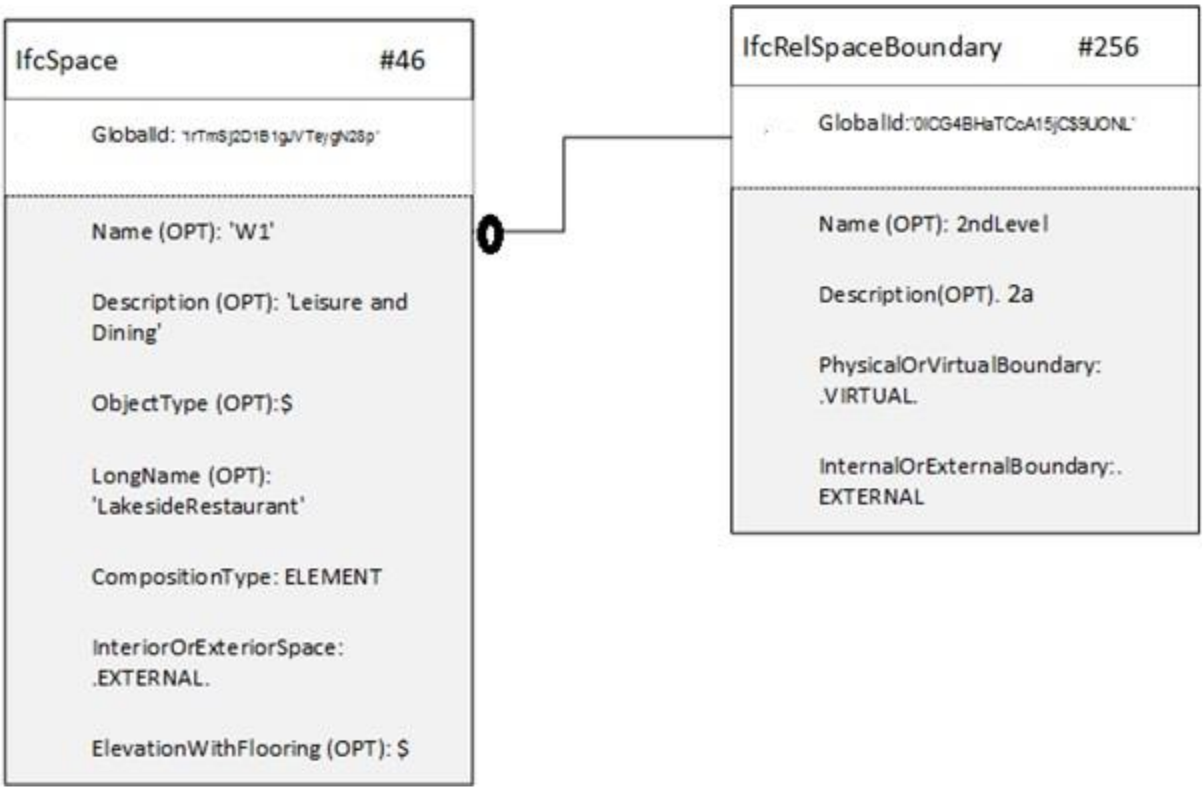


Figure 55 Extract from IFC model showing IfcSpace *with attributes for a conceptual mass of the Lake Restaurant. Note the fact that it is a virtual rather than a physical boundary and the 2a denoting* 2^{nd} *level space boundaries.*

7.4. Conclusion: Working with Open BIM Standards to Source Legal Spaces for a 3D Cadastre

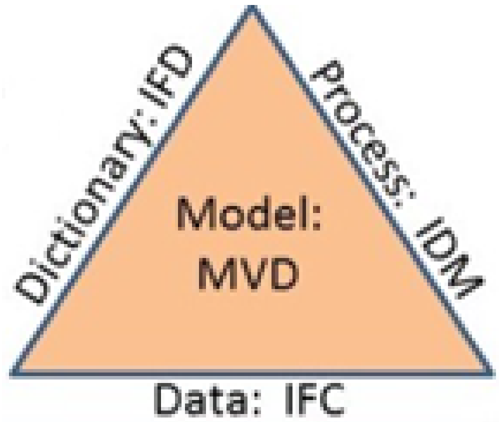


Figure 56 the main BuildingSmart standards

The title of this thesis 'Working with Open BIM Standards to Source Legal Spaces for a 3D Cadastre' reflects the use of BuildingSMART standards throughout it. The IFC was the lynchpin of this work; studying its many entities, learning to model it in its graphic form – ExpressG, and then finding a way to map it to the LADM. Although the LADM is a conceptual model, and the IFC an exchange format, it is possible to map them to each other. This has been done in a way which is does not prescribe the exchange format, with files created in architectural software and stored in .ifc files.

Mapping the IFC to the LADM meant working with another BIM open standard, the MVD. The MVD involves narrowing the IFC down to provide a framework in which objects can be made. This complexity of this task is confirmed by the fact that there is a tool, the IfcDoc, which facilitates the process and produces a .xml file so that communication can be automated.

The set of requirements defined by the MVD is something which can be used in an automated workflow, modelled using a third open BIM standard – the IDM. The IDM is more than a workflow modelled in Business Process Modelling Notation, but it was on this part of the standard that this thesis has concentrated. The workflow which forms the second half of the paper is based, in part, on the difficulties experienced in creating a legal space for the Lake Restaurant. Communicating cadastral requirements early in the design process would facilitate the process of obtaining legal spaces from BIM. While in many cases spaces can simply be extracted from BIMs at the end of the design process, legal spaces could also be defined at the beginning of the design process. Requiring that a 3D volume of the plan of the building be sent to the cadastre for testing early on would ensure the presence of topological legal spaces for use by the cadastre. It is also a way to check that the building is being designed and built within cadastral regulations – the rights, restrictions and responsibilities associated with the spatial unit.

7.5. Conclusion: Future Work

Although the *.ifc* files generated included the requirements for a Cadastral Model View Definition, they also included a lot more. This is due to the Archicad environment in which they were made, but is also something which occurred with Revit files. Further research could look at how these files could be filtered to take out unnecessary details.

LADM packages beyond the Spatial Unit package were not dealt with in this thesis, although much data, for example administrative, could easily be sourced from BIM files. Another issue which could be explored is how to obtain versioned objects from the IFC. Future work could focus on this.

The use cases illustrate simple volumes, whereas the reality as illustrated by the Delft train station Figure 5 is far more complex. Further use cases could be made which more closely illustrate as built volumes.

A workflow is a not a static object but a work in progress. Further effort could be put in to test and develop the work flow. Ideally this would be in conjunction with the *Kadaster* itself.

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Appendix 1: Interviews

Industry Perspectives

John Schapendonk Accountant (*Financial Controller*) at *Van der Panne* Rotterdam
http://steigerbouw.nl/ and formerly of *Van Wijnen* Rosmalen
https://www.vanwijnen.nl/

Main points that he made:

- Projects of 10 million euros and above are now being made with Building Information Models and that in fact the recession has stimulated the increased use of BIMS rather than hindered it. This is due to the 10% of the budget which is lost due to mistakes being made during building projects. BIMs are helping to narrow this figure.

- That increasing numbers of building projects are being purchased with an accompanying maintenance contract. This is because purchasers believe that a better quality product will then be delivered - the maintenance costs on a shoddily built building would be far higher than on a well built one.

- The company which maintains the building is not the owner of the BIM. This stays in the hands of the owner of the building. This is in case the maintenance company goes bankrupt.

IFC Perspective

Thomas Krijnen PhD Candidate Department of the Built Environment TU Eindhoven
http://thomaskrijnen.com/

- Gave insights into the structure of the IFC schema

- Suggested the use of property sets and key values in order to link the IFC to the LADM

- Described the use of key value stores in property sets