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a prerequisite for a digital information flow for applications in the planning and building sector

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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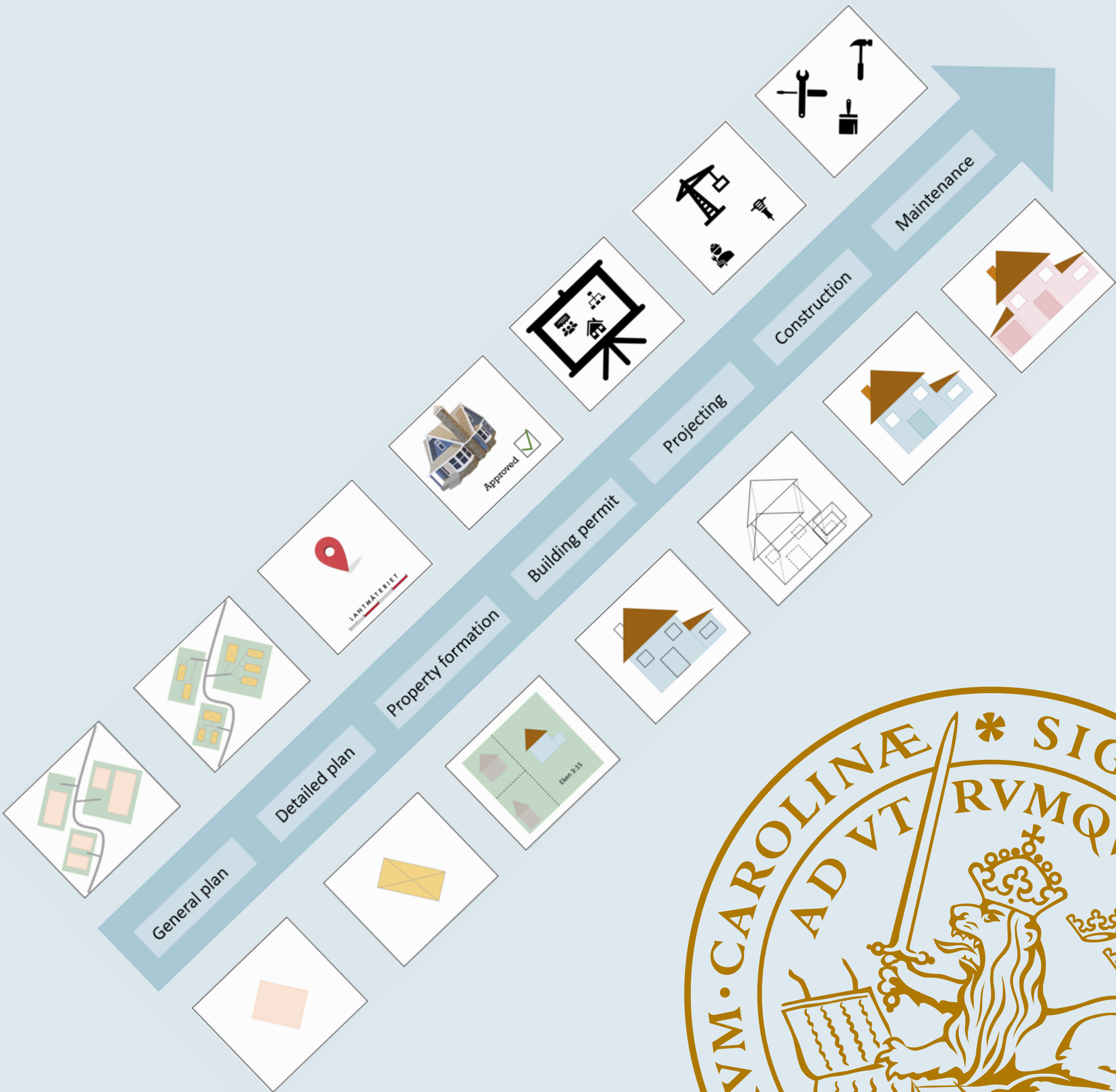
HELEN ERIKSSON

DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY



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Harmonisation of 3D geodata

– a prerequisite for a digital information flow for applications in the planning and building sector

Helen Eriksson

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Abstract

Data harmonisation is a prerequisite for smart cities, for a more efficient information flow in the planning and building process and for many applications in the urban environment. Ideally, data harmonisation will result in a digital information flow that include information from the whole lifecycle of a feature, for example for buildings, roads and tunnels. All actors and applications involved in this process should be able to retrieve the information they require. This in turn contributes among others to the development of more sustainable cities and to reduce the shortage of housing, which is an issue in many urban areas around the world. There are still many obstacles to overcome before such well-functioning digital information flow can be achieved. In this thesis harmonisation of geographic data is studied from different technical perspectives, that is data harmonisation between geographic levels, between hierarchic structures, and over time

Standards for geographic data often focuses primarily on a certain geographic level. Examples of this are the INSPIRE directive with the main focus on cross-border applications at a European level; and the Swedish water system standard that has a national focus. That is, there are no harmonisation between the geographic levels. In Paper I we extended the INSPIRE specification for hydrography with all additional information in the Swedish water system standard to evaluate if this would achieve a more harmonised information exchange between geographic levels from both a user and a data provider perspective.

Papers II – VI have a focus on 3D building information in the planning and building process and on how the digital information flow within this process can be improved for urban environment applications. 3D building information is an important part of this process and much would be gained if digital standardised information is easily available throughout the lifecycle of the building. In Paper II we evaluated the consequences of having similar but not identical definitions in standards that are related. In Paper III we created and evaluated whether guidelines could contribute to a more uniform creation of datasets, regardless of which data source is used. Paper IV is devoted to a proposal to a national building standard. It is based on national requirements and international standards and an evaluation is performed to see if this could contribute to a more uniform management of 3D city models within a country. Paper V evaluated if currently available versioning methods for 3D city models can fulfil requirements from applications in the planning and building process, and if all versioning methods are suitable for all purposes. Finally, in Paper VI we evaluated what is required and what are the issues that must be solved before versioning methods for 3D city models are used in practice, as versioning methods currently are available, but are rarely used.

To conclude, this thesis has described, developed and evaluated how harmonisation of geographic data can improve the digital information flow. The main focus was on 3D building information in the planning and building process, but most of the findings are also applicable on other types of information, especially on 3D city models and on other man-made themes such as roads, tunnels and bridges. The results give an increased understanding about issues that must be solved to achieve an efficient digital flow of geographic information. It also points out the importance of performing detailed requirements analyses on application needs before implementation and that the usage of guidelines can contribute to a more streamlined usage of standards.

Key words
Data harmonisation, schema extension, 3D buildings, 3D city models, GeoBIM, lifecycle and version management, temporal information, user requirements, guidelines, hydrography

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Helen Eriksson

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To Arvid and Tilda

Abstract

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To conclude, this thesis has described, developed and evaluated how harmonisation of geographic data can improve the digital information flow. The main focus was on 3D building information in the planning and building process, but most of the findings are also applicable on other types of information, especially on 3D city models and on other man-made themes such as roads, tunnels and bridges. The results give an increased understanding about issues that must be solved to achieve an efficient digital flow of geographic information. It also points out the importance of performing detailed requirements analyses on application needs before implementation and that the usage of guidelines can contribute to a more streamlined usage of standards.

Sammanfattning

Dataharmonisering är en förutsättning för smarta städer, för ett mer effektivt informationsflöde i samhällsbyggnadsprocessen och för många andra tillämpningar i en stadsmiljö. Vid ett bästa tänkbart scenario kommer dataharmonisering att resultera i ett digitalt informationsflöde som inkluderar information från ett objekts hela livscykel, till exempel för byggnader, vägar och tunnlar. Alla aktörer och applikationer som är involverade i denna process ska då kunna hämta den information som de behöver. Detta bidrar i sin tur bland annat till utvecklingen av mer hållbara städer och till att minska bristen på bostäder, vilket är ett problem i många städer runt om i världen. Det finns dock fortfarande många hinder att övervinna för att kunna uppnå ett sådant välfungerande digitalt informationsflöde. Denna avhandling studerar harmonisering av geografiska data från olika tekniska perspektiv, det vill säga dataharmonisering mellan geografiska nivåer, mellan hierarkiska strukturer och över tid.

Standarder för geografiska data fokuserar ofta främst på en viss geografisk nivå. Exempel på detta är INSPIRE-direktivet med huvudfokus på tillämpningar som berör flera länder på en europeisk nivå, och den svenska vattensystemstandarden som har ett nationellt fokus. Det vill säga det finns ingen harmonisering mellan de geografiska nivåerna. I den första artikeln (Paper I) utökade vi INSPIRE-specifikationen för hydrografi med all ytterligare information som finns i den svenska vattensystemstandarden för att utvärdera om vi i och med detta skulle uppnå ett mer harmoniserat informationsutbyte mellan geografiska nivåer ur både ett användar- och ett dataleverantörsperspektiv.

Artiklarna två till sex (Paper II – VI) fokuserar på den 3D-byggnadsinformation som används inom samhällsbyggnadsprocessen samt på hur det digitala informationsflödet inom denna process kan förbättras för tillämpningar inom detta område. 3D-byggnadsinformation är en viktig del av denna process och mycket skulle förbättras om digital standardiserad information är lättillgänglig under byggnadens hela livscykel. I artikel två (Paper II) utvärderade vi konsekvenserna av att ha liknande men inte identiska definitioner i olika relaterade standarder. I artikel tre (Paper III) skapade och utvärderade vi om riktlinjer kan bidra till att datamängder kan skapas på ett mer enhetligt sätt, oberoende av vilken datakälla som används. Artikel fyra (Paper IV) beskriver ett förslag till en nationell byggnadsstandard. Den baseras både på nationella krav och på internationella standarder och en utvärdering görs för att se om detta kan bidra till en mer enhetlig hantering av 3D-stadsmodeller

inom ett land. I artikel fem (Paper V) utvärderades om nu tillgängliga versioneringsmetoder för 3D-stadsmodeller kan uppfylla kraven från tillämpningar inom samhällsbyggnadsprocessen, samt om alla versioneringsmetoder är lämpliga för alla typer av ändamål. Slutligen, i artikel sex (Paper VI) utvärderade vi i vad som krävs och vilka frågor som måste besvaras för att versioneringsmetoder för 3D-stadsmodeller ska kunna användas i praktiken, eftersom versioneringsmetoder nu finns tillgängliga men ändå sällan används.

Avslutningsvis har denna avhandling beskrivit, utvecklat och utvärderat hur harmonisering av geografiska data kan förbättra det digitala informationsflödet. Huvudfokus har varit på 3D-byggnadsinformation i samhällsbyggnadsprocessen, men de flesta resultat gäller även för andra typer av information, framför allt för 3D-stadsmodeller och andra konstgjorda objekt så som vägar, tunnlar och broar. Resultaten ger en ökad förståelse för de frågor och problem som måste lösas för att uppnå ett effektivt digitalt flöde av geografisk information. De pekar även på vikten av att utföra detaljerade kravanalyser på tillämpningars behov innan implementering samt på att användandet av riktlinjer kan bidra till en mer ändamålsenlig användning av standarder.

Acknowledgement

During the last decade I have been working with harmonisation and standardisation of geographic data in many projects at Lantmäteriet. I enjoyed my work and also saw an increasing need in society for such harmonisation. When the opportunity came for a post as an industrial PhD at Lantmäteriet, studying harmonisation of geographic data, I applied for it. I would like to thank Lantmäteriet for making this possible, it has been a great opportunity for me to do this.

Coming back to the academy after 25 years was a challenge for me that required a completely different way of thinking. I would like to give my warmest thanks to my supervisor Lars Harrie for his guidance back into the academic world and the whole way to a PhD. His skills to see possibilities in everything is amazing. I came to him many times with problems unsolvable for me and after very constructive discussions I left with a smile and a new way forward. I would not have been able to come this far without his support. My co-supervisor at Lantmäteriet, Jesper Paasch, has also been a great support. His positive attitude to everything and his many constructive comments on my work has definitely helped me move forward.

Studying as an adult is very different from when I first studied at the university. I guess it is a bit more difficult and time consuming to learn new things, but you have much more experiences that you can connect your studies to, and it is also much more enjoyable. Even though I have been working on distance from Kiruna most of the time, I have met so many nice and skilled PhD students during my four years of studies in Lund, no one mentioned no one forgotten. It has been a pleasure meeting you all and I have enjoyed our interesting discussions.

Having my desk at the GIS centre has also been special, a small world of its own, in a very good sense. My “roommates” Michel, Mitch and Roger, and all the others at the GIS centre: Petter for making it such a familiar place, and Abdulghani Ali, Andreas, Karin, Mahdi and Pearl, thank you so much for making me feel welcome each time I was in Lund.

Last but not least, I could not have done this without the support from my family. My parents who made me feel that nothing is impossible. Mom, I wish you were still here to share this with me. My husband Sven who has always believed that I would make it even when I had my doubts and my children Arvid and Tilda, you are the joy of my life.

Table of Contents

1 Introduction

1.1 Motivation

An infrastructure with digital information flows is a precondition for smart cities, for a more efficient planning and building process and for applications in the urban environment. This can in turn be important for the development of more sustainable cities and to overcome the shortage of housing which is an issue in many urban areas around the world. Having a well-functioning digital information flow is often taken for granted, but is not always the case. An important prerequisite to achieve this digital information flow is harmonised data. Data harmonisation is a very broad area and includes technical, organizational, legal, business and educational aspects.

From a technical perspective, harmonised data is the result from a data harmonisation process where data of varying file formats, structures, attributes and naming conventions are transformed into a harmonised dataset that conforms to a specification or standard. Important driving factors for the harmonisation of geographic data during the last decade are for example the implementation of the INSPIRE Directive (Directive 2007/2/EC, 2007) in all EU member states; the development of spatial data infrastructures (SDIs); the requirements on a more effective digital information flow in the planning and building sector; and the increased demand for 3D city models around the world.

The implementation of the INSPIRE Directive started in 2010 and has driven the development and increased the knowledge of SDIs at European, national and regional levels. To fulfil the directive, all EU member states should provide harmonised geographic data for the 34 INSPIRE themes through network services (discovery, view and download), following the requirements in the technical guidelines for network services. At the same time, the demand for easily available geographic information is increasing in society; thus, many countries now recognize a need to also provide more detailed geographic information at the national or regional levels that is not included in the INSPIRE directive. One possible means of realizing this goal is to extend INSPIRE data specification to include more detailed and specific national information.

In the planning and building process today, data is not always shared between actors involved and between the different phases (e.g. planning, real property formation and construction). When data is shared, the handover between the phases is not always standardised, and the information could either be digital or printed copies. The demand for a standardised and digital information flow is growing, especially as this is seen as one of the means to make the planning and building process faster and more effective. This could for example enable various automated processes, such as for building permits, which in turn can contribute to a shorter construction time and by that be part of the solution to the shortage of housing.

During the last decades 3D city models have become increasingly common, especially in larger cities. Already in 2012 there were more than a thousand city models worldwide (Morton et al., 2012) and the number is growing (Biljecki et al., 2015, Julin et al. 2018). 3D city models often comprise of information from various geographic themes (e.g. buildings, roads, bridges, city furniture and vegetation) that are harmonised to a standard, such as CityGML (Gröger et al., 2012) or CityJSON (Ledoux et al., 2019). Reasons for creating 3D city models vary, earlier the models were mainly used for visualization, but now they are used for other purposes as well, such as urban planning, decision making, analyses, and to replace the 2D base maps in urban areas, which requires that the city models have connections to e.g., cadastral registers. To be able to support these applications, new requirements are emerging on the 3D city models, for example be the need for new national standards to obtain a more uniform management of the building information within a country, or the need to include temporal information and version management in the 3D city models.

The above descriptions show various examples of where data harmonisation is required. Data harmonisation and the sharing of this information are complex, and from a technical point of view, many aspects can be improved. This thesis focus on some of these aspects: harmonisation between geographic levels; how different and ambiguous definitions of data hierarchies can affect data exchange within and between specifications; and how temporal information and versioning can contribute to a more process-oriented information flow with information about real-world objects during their whole lifecycle.

Another important aspect for data harmonisation is the specifications and standards that the information should conform to in order to become more standardised and harmonised. For example, many 3D city models do not live up to their expectations, such as missing information content (Julin et al., 2018) is not versioned at all (Vitalis et al., 2019), or are difficult to use in software tools (Noardo et al., 2020c). A reason to why some 3D city models do not meet their expectations could be that no proper requirements analysis were conducted. This thesis also evaluates the role of requirements analyses and how guidelines can be used to guide users to use comprehensive standards in the intended way. Last but not least the thesis examines reasons for why versioning methods for 3D city models that exists and would improve their usability still is not used in practice.

1.2 Research questions and objectives

The overall research question for this thesis is *how harmonisation of geographic data can contribute to a more efficient digital information flow* with a special attention on serving the needs of applications in the planning and building sector. Data harmonisation is a broad area that can be perceived in various ways and can be seen from different perspectives. This thesis focus on technical aspects of the harmonisation of geographic data, more specifically: between geographic levels, between hierarchic structures, and over time. Within this framework the following specific research questions were formulated:

1. Different geodata standards are often used at different geographic levels (e.g. European, national and regional).

   Can the extension of a European specification with detailed national information achieve a more harmonised information exchange between these level?

2. The definition of concepts in a standard can be ambiguous and described as recommendation instead of requirements. Related standards can also share concepts that have almost the same definition.

   What are the consequences of having similar but not identical definitions? Can the use of guidelines contribute to a more uniform creation of datasets?

3. The number of 3D city models are increasing worldwide and the requirements on their usage are becoming more complex: from previously being visualisation only, to use in analysis and in simulations for decision making in various applications such as urban planning. Still many 3D city models do not meet expectations and 3D city models within a country are not conformant.

   Can a national standard based on national requirements and international standards contribute to a more uniform management of 3D city models within a country?

4. The use of 3D city models in different phases of the planning and building process entails that the models are versioned as this is a requirement from for example building permit and 3D cadastre applications.

   Do currently available versioning methods for 3D city models fulfil requirements from applications in the planning and building process? Can all methods be used for all purposes?

5. The number of 3D city models that are used in advanced applications are increasing. This often requires that the models are linked to other geodata models and registers and that they include temporal information and are

continuously updated. Even though versioning methods for 3D city models exist, most models have no version management, and a large part of the openly available models are not changed at all.

What is required and what are the issues that must be solved for the versioning methods to be used in practice?

The aim of this thesis is to define prerequisites for achieving a more efficient digital flow of geographical information, with a main focus on the planning and building process. The hypothesis is that this can be achieved by harmonisation of geographical information, and in this thesis the viewpoints between geographic levels, between hierarchic structures, and over time are studied. The aim consists of six research objectives and each of them corresponds to one paper:

1) to study techniques for creating formal extensions of INSPIRE specifications and to evaluate the consequences of using extended INSPIRE dataset from both a user and a data provider perspective (Paper I)
2) to study how building parts are defined in specifications, to describe potential use of building parts, and consequences of the usage of them (Paper II)
3) to create modelling guidelines for constructing 3D geodata building models to be used irrespective of the data source (Paper III)
4) to develop and evaluate a proposal for a national building standard in Sweden (Paper IV)
5) to compare and evaluate three version management methods for 3D city models (Paper V)
6) to identify obstacles to version management of 3D city models, and to propose recommendations on how to overcome these obstacles (Paper VI)

1.3 Limitations

This thesis mainly focus on the digital flow of geographical information in the planning and building process, and within this process mainly on 3D building information. The main reason for this is that there is a strong interest in society to streamline and automate the planning and building process as a more efficient process could be a solution to shortage of housing in many urban areas, and also be beneficial to many other urban environment applications. To achieve this the information flow must, among others, be more harmonised. An important part of this is 3D building information and much would be gained if digital standardised information that contain the required information could be easily available throughout the lifecycle of the building.

It must also be noted that even though 3D building information is used in a majority of the studies in this theses, the outcome is applicable also to other geographic themes, especially on 3D city models and on other man-made themes such as roads, tunnels and bridges.

1.4 Thesis organisation

This thesis is organised in five chapters with six appended papers. Chapter one describes the motivation, research questions and objectives, and limitations of the study. Chapter two describes the background for this thesis. Here the terms harmonisation, standardisation and interoperability are described, examples of applications for 3D city models are presented, and standards for the planning and building are described. Chapter three describes related work for this thesis. It includes different methods to extend existing specifications; issues with the integration between Building Information Modelling (BIM) and geodata; conformance testing; interoperability challenges in current open standards; and lifecycle and versioning methods used in different areas. In chapter four the papers included in the thesis are summarised. Finally, in chapter five the main conclusions and outlooks are provided.

The six papers included in the thesis are:

1.4.1 List of papers

I. **Eriksson, H**., Harrie, L., Paasch, J. M., Persson, A. (2018). Techniques for and consequences of using INSPIRE extensions: a case study with Swedish hydrological data. *Int. J. Spat. Data Infrastruct. Res.*,13, 172-201. http://ijsdir.jrc.ec.europa.eu/index.php/ijsdir/article/view/471

II. **Eriksson, H**., Harrie, L., Paasch, J. M. (2018). What is the need for building parts? - A comparison of CityGML, INSPIRE Building and a Swedish building standard. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, Volume XLII-4/W10, 27–32. doi: https://doi.org/10.5194/isprs-archives-XLII-4-W10-27-2018

III. Sun, J., Olsson, P.-O., **Eriksson, H**., Harrie, L. (2019). Evaluating the geometric aspects of integrating BIM data into city models, *J. Spat. Sci*. doi: https://doi.org/10.1080/14498596.2019.1636722

IV. **Eriksson, H**., Johansson, T., Olsson, P.O., Andersson, M., Engvall, J., Hast, I., Harrie, L. (2020). Requirements, Development, and Evaluation of a National Building Standard – A Swedish Case Study. *Isprs Int. J. Geo-Inf.*, 9, 78. doi: https://doi.org/10.3390/ijgi9020078

V. **Eriksson H**., Sun J., Tarandi, V., Harrie, L. (2020). Comparison of versioning methods to improve the information flow in the planning and building processes, *Trans. GIS*. doi: https://doi.org/10.1111/tgis.12672

VI. **Eriksson H**., Harrie L. (2020). Versioning of 3D city models – needs, obstacles and recommendations (Submitted)

1.4.2 List of contributions

I. **HE** planned the study together with LH and carried out most of the practical part. AP performed part of the user tests. **HE** interpreted the results together with the co-authors and did most of the writing.

II. **HE** planned the study together with LH and carried out the practical part. **HE** evaluated the results together with the co-authors and did most of the writing.

III. JS and LH planned the study and JS did most of the writing. **HE** created the modelling guidelines used in the study.

IV. **HE** planned the study together with LH, performed the inventory parts and did most of the writing . **HE** performed the UML modelling with MA and JE and the creation of the XSD file together with IH.

V. **HE** planned the study together with LH and performed two of the test cases. VT performed the third test case and JS created the test data. **HE** interpreted the results and did most of the writing.

VI. **HE** planned the study together with LH and performed the interviews and test cases. **HE** interpreted the results and did most of the writing.

1.4.3 Related papers

Olsson, P., Johansson, T., **Eriksson, H**., Lithén, T., Bengtsson, L.H., Axelsson, J., Roos, U., Neland, K., Rydén, B., Harrie, L. (2019). Unbroken digital data flow in the built environment process - a case study in Sweden. *In Proceedings of the ISPRS Geospatial Week*, Enschede, The Netherlands, 10–14 June 2019, Volume XLII-2/W13.

Noardo, F., Krijnen T., Arroyo Ohori, K., Biljecki, F., Ellul, C., Harrie, L., **Eriksson, H**., Polia, L., Nebras Salheb, N., Tauscher, H., van Liempt, J., Goerne,

H., Hintz, D., Kaiser, T., Leoni, C., Warcho, A., Stoter, J. Reference study of IFC software support: the GeoBIM benchmark 2019 — Part I (Submitted 2020) https://arxiv.org/pdf/2007.10951.pdf

Noardo, F., Arroyo Ohori, K., Biljecki, F., Ellul, C., Harrie, L., Krijnen, T., **Eriksson, H**., van Liempt, J., Pla, M., Ruiz A., Hintz, D., Krueger, N., Leoni, C., Leoz, L., Moraru, D., Vitalis, S., Willkomm, P., Stoter, J. Reference study of CityGML software support: the GeoBIM benchmark 2019 — Part II (Submitted 2020) https://arxiv.org/pdf/2007.10938.pdf

Noardo, F., Harrie, L., Arroyo Ohori, K., Biljecki, F., Ellul, C., **Eriksson, H**., Guler, D., Hintz, D., Jadidi, M.A., Pla, M., Sanchez, S., Stouffs, R., Tekavec, J., Stoter, J. (2020). Tools for BIM-GIS Integration (IFC Georeferencing and Conversions): Results from the GeoBIM Benchmark 2019. *Isprs Int. J. Geo-Inf.* 9, 502, doi:10.3390/ijgi9090502

2 Background

2.1 Harmonisation, standardisation and interoperability

There is no general consensus in the definition of the terms *data harmonisation* and *data standardisation*, and the terms are often used interchangeable when describing a process of bringing data of varying file formats, naming conventions, attributes etc. into a common data format. Some sources describe a difference though, The Centre for Trade Facilitation and E-business of the United Nations (UN/CEFACT) has developed data harmonisation guidelines and defines data harmonisation as an iterative process where government information requirements is captured, defined, analysed and reconciled, while data standardisation is defined as the mapping of these harmonised data to international standards (UNCEFACT, 2012). Richen and Steinhorst (2005), describe standardisation as the creation of a uniform business processes across various divisions or locations while harmonisation is to prevent or eliminate differences in the technical content of standards having the same scope.

In the INSPIRE Generic Conceptual Model (GCM; 2014), data is considered to be harmonised if the underlying conceptual models and the associated datasets are restructured according to the INSPIRE specifications. If the data only is transformed to this common format before it is provided through network services, *interoperability* is enabled. By this the data is represented in a format that allows it to be combined it with other interoperable spatial datasets in a coherent way.

The network services mentioned above is part of the spatial data infrastructure (SDI) that the INSPIRE Directive aims to create for environmental policies and activities that have an impact on the environment at a European level (Directive 2007/2/EC, 2007). An SDI is often defined as a "collection of technologies, policies and institutional arrangements that facilitate the availability of and access to spatial data" (Nebert, 2004) and exists on many levels. At the global level, the Global Spatial Data Infrastructure (GSDI) Association[1] promoted international cooperation and collaboration in support of SDI research and implementations. GSDI was dissolved in 2018 as its role to a large extent had been taken over by the Open Geospatial Consortium, United Nations, and the World Bank.

[1] http://www.gsdi.org/

The data interoperability that SDIs attempt to achieve includes, according to the INSPIRE GCM (2014), of 20 components that contributes to different aspects of the interoperability, figure 1. The INSPIRE Methodology for the development of data specifications (2008) is in turn based on these components. This ensures that the data specifications for the 34 INSPIRE theme are harmonised as they are developed using the same methodology. According to the INSPIRE GCM (2014), the main solution for the foreseeable future is to achieve data interoperability through harmonised data specifications on the European level rather than harmonising the data in the Member States.

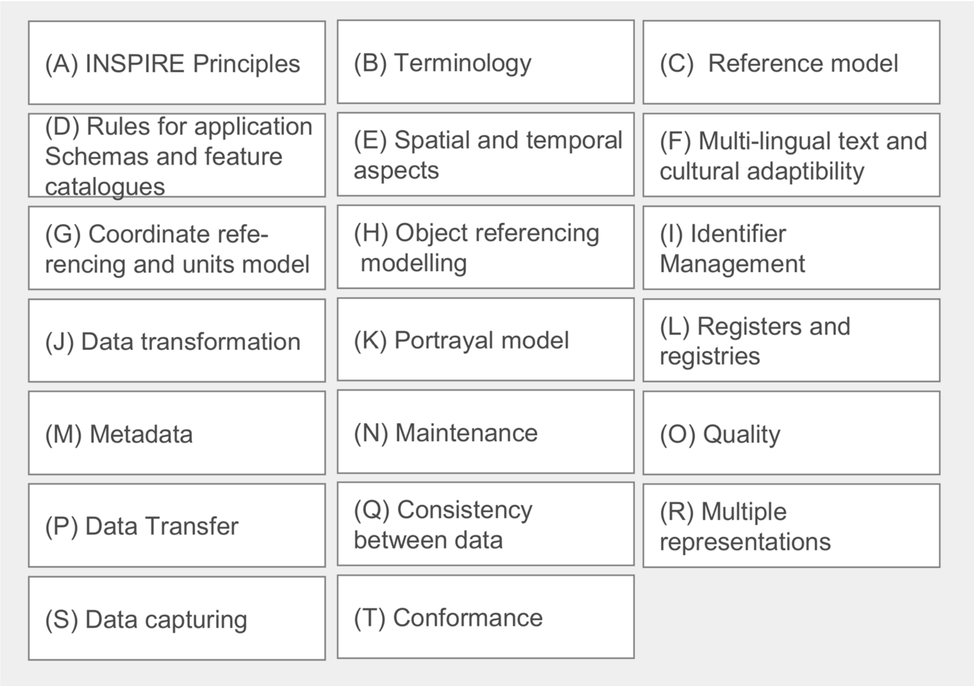

Figure 1 *Overview of data interoperability components (from INSPIRE, 2014)*

The technical development of SDIs and data interoperability heavily rely on international standards from the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC). The ISO 19000 series (ISO 19101 to ISO 19162) covers the areas of digital geographic information and examples of standards used in the SDI and data interoperability development are *Geographic information – Data product specification* (ISO 19131:2007) and *Geographic information – Metadata* (ISO 19115-1:2014). The standards for network services were originally developed by OGC, but have now also become ISO standards through joint development in the ISO/TC 211 committee. Examples of such standards are *Geographic information – Web map server interface* (ISO

19128:2005) for view services and *Geographic information — Web Feature Service* (ISO 19142:2010) for download services. OGC has recently developed a new standard, *OGC API - Features - Part 1: Core* (OGC API, 2019), that includes among others the same functionalities as the web feature service, but using a more modern technology.

2.2 Applications of 3D city models

Requirements for a more effective planning and building process is a strong driver for the development of 3D city models, as such information is needed in many phases of this process. Figure 2 describes the different phases of the planning and building process, from planning, property formation and building permits to projecting, construction and maintenance. Generally, the information within this process can be divided into two parts: phase specific information (i.e. information that only is used within one phase) and general information (i.e. information that is shared between different phases). The general information mainly consists of real-world objects that evolve over time. A building is for example the same real-world object in a detailed development plan, real property formation plan and during construction, but is described with different attributes and geometries. The information is modelled using both BIM (Building Information Modelling) and geodata.

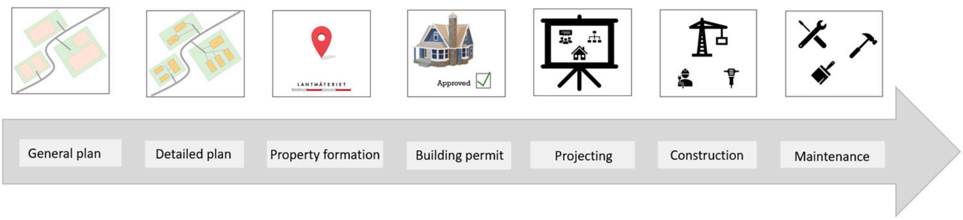

Figure 2 *Overview of the phases in the planning and building process*

There is an increased interest in streamlining the work within many of the phases in the planning and building process. The handling of building permits is for example often seen as a phase that prolongs the whole construction time. Information, such as detailed development plans and building permit regulations, are still often shared in paper format or as pdf files (Benner et al., 2010; van Berlo et al., 2013; Olsson et al., 2018) and can make the process ineffective, concerning both time and cost. Much would be gained if the work process were more standardised and had a process-oriented approach where all actors can share information. Such an approach was proposed within the EuroSDR GeoBIM benchmark project[2] (Noardo et al., 2019) where the current building permit process was studied in the participating countries. Based on that, the project defined a workflow for information exchange in the building permit process where 3D building information is used to improve the rule checking of the building permit application. To enable this, the BIM-model of the proposed building was converted to geodata and integrated in a 3D city model. The updated 3D city model was then utilized both for visual inspection as well as in automated routines where the property of the building and the surrounding environments are tested against rules in a digital detail development plan (Olsson et al., 2018).

Another example of where 3D city models could improve the planning and building process is in 3D cadastre. The number of 3D property unit registrations has increased as a result of the high density of many cities and the need for better utilization of spaces, both within buildings and below ground (Paulsson and Paasch, 2013). Much of the cadastral information sharing between actors, such as architecture, engineering, and construction (AEC) companies, cadastral surveying units and city surveying units, is currently in non-machine-readable formats (e.g. pdf files). Furthermore, the 3D cadastre is still defined in 2D drawing and textual descriptions, and the cadastral index maps are still in most cases 2D maps (El-Mekawy et al., 2015). Several studies have used BIM models and 3D city models in the 3D cadastre process. Atazadeh et al. (2017) implemented three BIM-based models (purely legal, purely physical and integrated models) of multi-storey buildings to investigate their performance. The results illustrated that integrated models could provide a more visual communication of the location of legal boundaries. A BIM could be used for visualization of the extent of the 3D property units, but to get an overview of the 3D property units in larger areas, a city model is required. An example of this is the study by Góźdź et al. (2014) that visualize legal spaces in a levels of detail 1 (LOD1) city model based on a CityGML 2.0 application domain extension (ADE). The new proposed version 3.0 of CityGML (Kutzner and Kolbe, 2018; Kutzner et al., 2020) has taken 3D cadastre into account by providing a stronger connection to the Land Administration Domain Model (LADM; ISO 19152:2012). CityGML 3.0 also makes it possible to distinguish between physical and logical spaces, where the logical spaces could represent the legal spaces of the 3D cadastre. This possibility was used by Sun et al. (2019b) who established technical and legal solutions for sharing 3D cadastre information based on the open standards LADM, Industry Foundation Classes (IFC; ISO 16739:2013), and CityGML 3.0. Cadastre information was stored in LADM, and the physical extent of the cadastre units was stored in IFC. The IFC building and cadastre data were converted to CityGML 3.0 and integrated to an existing city model. This enabled

[2] https://3d.bk.tudelft.nl/projects/geobim-benchmark/project.html

visualization of the cadastre information on a city scale and for macro analysis of cadastre information, by linking CityGML 3.0 data to LADM.

Many cities around the world see a need for 3D city models, and the number is growing (Biljecki et al., 2015, Julin et al. 2018). There are several possible usages for such models, earlier they were mainly used for visualization, but now they are used in a broad variety of applications. Biljecki et al. (2015) performed a comprehensive literature review of how 3D city models are being used in different domains. The review describes a wide use and categorises the usage into 29 use case groups. One use case describes visualisation for communication purposes, but the vast majority describe different types of estimation analyses, such as for solar irradiation, energy demand, shadows cast by urban features and propagation of noise. Other types of use cases are for navigation, urban planning, 3D cadastre, emergency response, change detection and archaeology.

3D city models are often developed for a specific purposes and there are several examples in the literature of where CityGML schemas have been extended with domain specific information using so called application domain extension (ADE), see section 3.1.2. Nouvel et al. (2015) developed an ADE extension that includes information to store and manage data required for calculation of building energy flows. In Tegtmeier et al. (2014) the authors created an ADE extension with features for geotechnical work at construction sites. Kumar et al. (2017) identified a need to better compare the results from different noise studies. This could be facilitated by more standardised input and output data for noise simulations. To achieve this, the existing Noise ADE was extended, that is, also an ADE can be extended.

There are also examples of ADE:s that includes additional information by linking or including information from other standards. Li et al. (2016) created a CityGML-LADM ADE extension that includes detailed description of ownership of condominiums. It has links to the LADM standard (ISO 19152:2012) to facilitate the cadastral management. The CityGML Infra ADE developed by Kumar et al. (2019) includes additional information from the OGC standard LandInfra (OGC LandInfra /InfraGML, 2016) that is not included in CityGML. LandInfra includes valuable information, but the standard is rarely used and has no software support. The ADE and a transformation tool between the CityGML Infra ADE and InfraGML (the GML implementation of LandInfra) are expected to increase the usage.

As the need for 3D city models increase, many cities create their own models. Such models are often created in different formats and might lack updating possibilities and quality information. This, and new requirements on 3D building information resulted in the creation of a national standard for 3D buildings in Germany (Gruber et al., 2014). The standard is created as a CityGML 1.0 ADE, AvD-CityGM, that both limits and extends CityGML (Roschlaub and Batscheider, 2018). The AdV-

CityGML datasets are centrally stored in a 3DCityDb[3], an open source solution that includes a database schema for all thematic modules from CityGML. Also the Netherlands has created a national 3D standard. It was created as a CityGML 2.0 ADE, IMGeo-CityGML, and extends CityGML with all additional information from their 2D building dataset (2D IMGeo), including a link to the 2D geometry which makes it possible to store 2D and 3D data in the same model (Arroyo Ohori et al., 2018).

The functionalities and usability of 3D city models was analysed in a Finnish study where 19 3D city models in six Finnish cities were studied (Julin et al. 2018). Three criteria were used: 1) platform used, 2) data accessibility and regional data coverage, and 3) the use of as-planned information (e.g., BIM). 3D modelling experts from the cities were interviewed, and the possibility to find real-time information, to interact, and to better include stakeholders in the decision-making processes were described as important benefits. The 3D city models should also include lifecycle management to support different decision-making processes in the cities. Most of the studied 3D city models included small geographic areas and had limited functionalities, but this did not live up to user expectations. To capture all characteristics of a 3D city model, Julin et al. (2018) propose a concept for harmonizing 3D city modelling and should include three perspectives: 3D GIS, BIM, and computer graphics.

2.3 Standards for the planning and building sector

The use of standards ensures that information exchange is performed using standardised formats and with predefined definitions of the concepts. It also makes machine-to-machine data exchange possible. This section describes commonly used standards in the planning and building sector.

2.3.1 CityGML

The most comprehensive standard today for exchange of 3D city models is the CityGML standard by OGC (Liu et al., 2017, Gröger et al., 2012). The main focus of CityGML is to represent the geometric and semantic aspects of features in a city. To support this, CityGML contains an information model, divided into several sub-models of buildings, tunnels, city furniture, vegetation, etc. Furthermore, CityGML supports multiresolution modelling by including different levels of detail (LOD) where the geometry, topology, and semantics are described with varying complexity. The current version, CityGML 2.0 (Gröger et al., 2012) defines five

[3] https://www.3dcitydb.org

LODs (Figure 3a), from a digital elevation model (LOD0) to a detailed representation of both the interior and exterior of a building (LOD4).

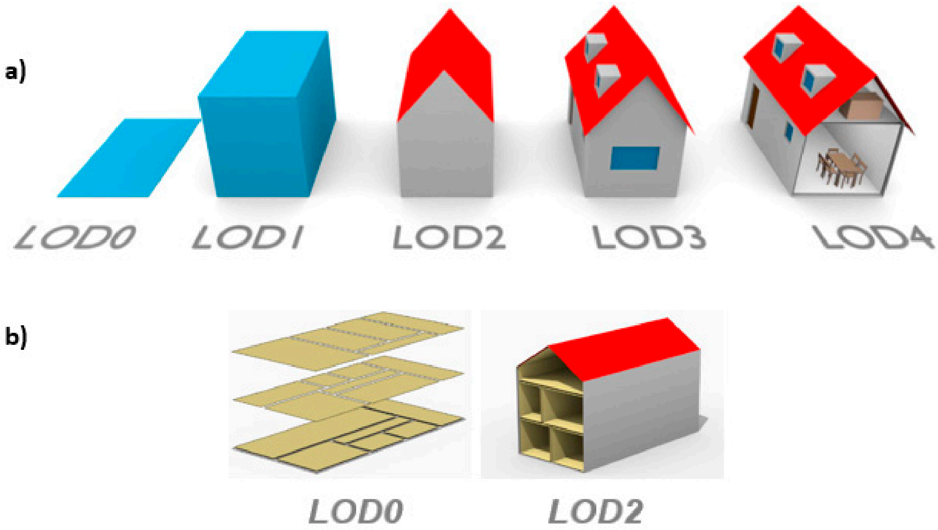

Figure 3 Examples of levels of detail (LOD) (a) in CityGML 2.0 (from Biljecki et al., 2014) and (b) in CityGML 3.0 (from Löwner et al., 2016).

CityGML is currently being revised both to increase the usage of the standard in different areas and to improve the interoperability with relevant standards such as IFC (ISO 16739:2013), LADM (ISO 19152:2012), and IndoorGML (Lee et al., 2016, Kutzner and Kolbe, 2018). In the new version, CityGML 3.0 (OGC CityGML3, 2019) the core model is restructured and extended and is now based on two abstract classes, *Space* and *SpaceBoundary*, to which all the geometric representations are associated. The LOD concept is also slightly modified. LOD4 is removed and instead both interior and exterior representations are allowed for all LODs, LOD0 to LOD3 (examples in Figure 3b). In addition, a new versioning module is developed having bitemporal timestamps for all objects and the possibility to have multiple versions of city models. It is also possible to describe time varying data for city objects and to integrate sensor data with 3D city models in the new *dynamizer* module.

2.3.2 CityJSON

CityJSON is a JSON implementation of a large subset of CityGML 2.0 (Ledoux et al., 2019, CityJSON, 2019). It is relatively new and is not an official OGC standard, but is under consideration for being approved as a community standard. JSON is used in many programming languages and it is one of the preferred formats for data exchange on the web. It includes three simple datatypes (strings, numbers, booleans) and two data structures: arrays, an ordered list of elements; and objects consisting of key/value pairs. An example of this is given in figure 4. In CityJSON, the CityGML 2.0 data model is flattened out and all hierarchies removed (Ledoux et al., 2019), following the structure of the database implementation of CityGML, 3DCityDB (Yao et al., 2018). The geometries in CityJSON are described using the same 3D geometric primitives as in CityGML, but with some restrictions that for example only allow for one way of representing the semantics and geometries of a feature.

```
"CityObjects": {
        "BU-01": {
        "type": "Building",
        "attributes": {
                "storeysAboveGround": 1,
                "function": "residential building"
                }
        "children": ["BUP-10", "BUP-20"]
        "geometry": [{...}]
        }
        "BUP-10": {
        "type": "BuildingPart",
        "parents": ["BU-01"]
        "geometry": [{...}]
        }
        "BUP-20": {
        "type": "BuildingPart",
        "parents": ["BU-01"]
        "geometry": [{...}]
        }
}
```

Figure 4 *Examples a CityJSON implementation of a building with two building parts*

The CityJSON data model is documented as JSON schemas and can also be used to validate CityJSON files. The schemas are openly available at https://cityjson.org/schemas/.

2.3.3 INSPIRE Building

The INSPIRE data specification for buildings (INSPIRE Building, 2013) is one of the 34 spatial data themes in the INSPIRE Directive (Directive 2007/2/EC, 2007). It is strongly influenced by CityGML 2.0 but also influenced by other standards (e.g., ISO 6707-1:2014 Building and Civil Engineering, DGIWG Feature Data Dictionary, and LADM, ISO 19152:2012), by use cases (e.g., for safety, environment, urban expansion, and infrastructures) and by current national databases. The building theme includes buildings and other constructions that are important for environmental applications, e.g., elevated constructions and environmental barriers.

2.3.4 Industry Foundation Classes – IFC

IFC is an open ISO standard (ISO 16739:2013, 2913) that specifies a conceptual data schema and an exchange format for BIM data and is developed and maintained by buildingSMART International[4]. It is a comprehensive and well-established standard that is implemented by a large number of software. The aim of IFC is to advance information exchange between different actors and programs without information loss. IFC describes the building information from the design, construction, and management phases. It includes for example building objects, such as walls, ceilings, doors for the architectural design; and pipes, air outlets, heaters, and valves for technical building equipment.

Requirements on the IFC model can be defined using the ISO standard Information Delivery Manual (IDM; ISO 29481-1:2010(E), 2010). The intention with this is to facilitate the interoperability between software applications used during the whole lifecycle of a construction. The IDM can be translated into Model View Definitions (MVDs) to create a subset of the IFC schema to delimit the IFC model for a certain purpose. MVDs can be encoded in a neutral and machine-readable format, mvdXML, that gives implementation-specific guidance of the structure and format.

2.3.5 Land Administration Domain Model - LADM

The LADM standard (ISO 19152:2012, 2012) describes among other things the part of the land registration that concerns the rights, responsibilities, and restrictions that affect land or water, and the geometrical representation of those objects. The standard supports 3D representation and is divided into four packages: *Party* – persons and organizations involved in the rights transaction), *Administrative* – rights, restrictions, responsibilities, and administrative units, *Spatial unit* – textual, point, area or volume representation of legal spaces for buildings, and utility networks, and *Surveying and representation* – surveying spatial sources and representing geometries and topology.

[4] https://www.buildingsmart.org/

2.3.6 LandInfra and InfraGML

LandInfra is an OGC standard for land and civil engineering infrastructure facilities (OGC LandInfra /InfraGML, 2016). It includes features such as roads, railways, land features, land division, survey, facilities, projects, and alignment. LandInfra describes the division of land based on *administrative* (jurisdictions and districts) and on *interests in land* (land parcels, easements, and condominiums). InfraGML is an OGC encoding standard that defines the GML encoding for LandInfra. It is published as eight parts: Core, LandFeature, Facility and Projects, Alignment, Road, Railway, Survey, and LandDivision.

3 Related work

3.1 Application Schema Extensions

Extending a specification is a way of providing more detailed information about a certain field and still provide most of the information in a standardised format. Another advantage is that the modelling does not have to start from scratch. There are primarily two standards that have attracted attention when it comes to extending specifications, the INSPIRE data specifications and the CityGML standard, but also CityJSON allow extensions. In order to create a formal extension, one should adhere to the established rules and recommendations.

3.1.1 INSPIRE extensions

An extended INSPIRE data specification is created as a new application schema with a unique namespace. The relevant INSPIRE schemas is imported into this schema. The INSPIRE GCM (2014) contains general rules on what is and what is not allowed when creating an extension. It is not allowed to add new classes, attributes or constraints within the INSPIRE base schema; or to add requirements that breaks requirements stated in the INSPIRE data specification. It is allowed add new feature types, associations and constraints to the new application schema and to extend extendable INSPIRE code lists.

An extension methodology on how INSPIRE extensions can be implemented was developed by Wetransform[5]. It gives a step by step description on how to create an extension together with design patterns and examples of existing INSPIRE extensions.

Network services that build on extended INSPIRE specifications and follow the INSPIRE extension rules are considered to be INSPIRE compliant; therefore, they will be treated as INSPIRE network services for this theme. If new elements are added as *optional* in the extended schema, the same web feature service (WFS) will be able to serve both INSPIRE extended and INSPIRE core GML files.

[5] http://inspire-extensions.wetransform.to/introduction.html

Many of the 34 INSPIRE specifications have been extended, and the reason for doing so varies. The European project European Location Framework (ELF) has developed specifications that extends INSPIRE specifications with additional features that is needed for cross-border and pan-European interoperability. The resulting datasets are provided via network services with a European coverage, from the 29 National Mapping and Cadastral Agencies in the 25 participating countries (Pauknerova et al. 2016). Fernández-Freire et al. (2013) see a need for more homogeneous cultural heritage information to be able to more easily share it and link it with other geographical information and created an extension for Protected Sites for this purpose. The extension also includes concepts from ISO 21127:2006 and the CIDOC Conceptual Reference Model (commonly used for description of heritage features). Another European project, HUMBOLDT, studied various data harmonisation solutions, especially concerning structural and semantic heterogeneities between different conceptual schemas. With that as a basis, they developed their own data harmonization process that also includes a set of tools (Fichtinger et al. 2011). One of the tools developed within the project, the Humboldt Alignment Editor[6] (HALE) has been further developed and are now widely used. The project tested their tools in two scenarios. In one of them, a flood risk management scenario, the INSPIRE Hydrography data specification was extended with information for risk management, following the extension rules in the INSPIRE GCM.

No descriptions of very complex extensions were found in the literature. In Paper I (Eriksson et al., 2018a) we examined if this is possible to do by creating a formal extension of the INSPIRE Hydrography (HY) specification. This extension contains all information from the Swedish water system standard SWSS (SS 637008:2015, 2015) that is not included in INSPIRE HY. Another aspect to take into consideration when developing an extension of a specification is the usability of the resulting dataset. To test this, the dataset resulting from the extended specification was evaluated from the perspectives of both users and data providers.

3.1.2 CityGML extensions

CityGML allows for schema extensions to include additional information. The schemas can be extended in two different ways, either by using generic city objects and attributes, or by creating an ADE (Gröger et al., 2012).

Generic city objects and attributes are realised by two classes in the CityGML schema, *GenericCityObject* and *_genericAttribute*. These are used to add new name-value pairs to existing city objects. An advantage with this is that the CityGML schema can be extended without changing the XML schema definition.

[6] http://www.dhpanel.eu/humboldt-framework/hale.html

Disadvantages are that there are no formal description of the added names and datatypes, only a few datatypes are available, naming conflicts can occur, and the generic objects and attributes cannot be validated in an XML parser.

An ADE is created as a new schema with its own namespace to which relevant CityGML classes are imported. Extensions can be done in two different ways:

- Create new classes that inherits from abstract or concrete CityGML classes (as it is done in INSPIRE extensions)
- Add attributes to existing CityGML classes, but where the new attributes belong to the ADE namespace. These attributes are described as *hook elements* in the XML schema definition file. The hooks are implemented as *_GenericApplicationPropertyOf <Featuretypename>* in GML. This method makes it possible to use many different ADEs simultaneously in the same CityGML feature (not allowed in INSPIRE extensions).

ADEs seems to be the most commonly used technique for extending CityGML and have been used in many different areas, Biljecki et al. (2018) provides for example an overview of 44 ADEs. These ADEs are mainly developed for applications that require special additional information not included in CityGML, but ADEs are also used to include national requirements to develop a national standard. Further examples of CityGML ADEs are described in section 2.2.

The proposed version 3.0 of CityGML also allows for schema extension, but no such extensions were found in the literature. In Paper IV (Eriksson et al., 2020a) we develop and evaluate a proposal for a new Swedish national 3D building standard as a CityGML 3.0 ADE. Reasons for choosing version 3.0 were that the new features included (e.g. the possibility to distinguish between physical and logical spaces for geometric representations, a new module for versioning, and a new object type, *BuildingConstructiveElement*, to map objects directly from IFC) were of significance for Sweden, but additional national information was also needed and therefore an ADE was created.

3.1.3 CityJSON extensions

It is possible to extend CityJSON with additional information. The following types of extensions are allowed: to add new complex attributes to an existing object; create or extend an object; and add new properties at the root. The extensions are stored in separate JSON files.

3.2 BIM and geodata integration

A well-functioning integration between BIM and geodata is essential for a digital information flow in the planning and building process as BIM and geodata models of the same real-world objects often exist. Both BIM and geodata is needed as one technique is not always enough to meet all requirements during the lifecycle of a building. Many issues may arise when performing this integration though, and the main reason for this is that BIM and geodata are originally developed for different purposes and by actors from different fields. This often result in models that represent, handle and threat data in different ways, which in turn can complicate the integration.

An attempt to overcome these integration issues at a conceptual level is made in the proposed ISO technical specification, Geographic information — BIM to GIS conceptual mapping (B2GM; ISO/TS 19166), which now is in its approval stage with a release date set for mid-2021. It proposes a conceptual framework for object mapping from a BIM model to a GIS model and contains three packages: *BIM to GIS Perspective Definition* – describing what BIM, GIS and external data that is included in a specific use case and how it should be extracted and integrated; *BIM to GIS Element Mapping* – describing the object mapping mechanism (ruleset) for conversion from BIM to GIS for a specific use case; and *BIM to GIS LOD Mapping* – describing a method to convert BIM to GIS at a certain LOD, for a specific use case, as defined in a LOD mapping ruleset.

Isikdag and Zlatanova (2009) performed a SWOT (Strength, Weakness, Opportunity, Threat) analysis that describes, from a technical viewpoint, the strengths and weaknesses of implementing BIM in a GIS environment. Further, the opportunities and threats of why the integration is done and how it is used is evaluated. Table 1 gives an overview of their results and, according to various studies, many issues still remain even though these results are from 2009.

Liu et al. (2017) have classified the integration of BIM and geodata into three categories: data level, process level and application level. A comparison of the effectiveness (less information loss), extensibility (high degree of openness), effort (time, labour and money cost) and flexibility (possibility to use results from one study in another) was performed. The results show that different methods are suitable for different purposes, but an integration at the data level with a semi-automatic conversion and translation, and extension of existing standards could be a good compromise.

Table 1 ASWOT Matrix for the implementation of BIMs in geospatial context (from Isikdag and Zlatanova, 2009)

The SWOT Matrix		
	Strengths	**Weaknesses**
Technical Perspective	• 3D Representation of Building Geometry • Spatial Hierarchy represented within an Object Oriented Data Model • BIMs contain Rich Semantic Information • Evolving Model that represents the Current State of the Building • Query based representation of indoor geometry • Clear space subdivision	• Differences in geometric representation of objects in AEC and Geospatial Information Domains • BIMs use local and relative coordinates • Spatial relationships are not stored in form of connectivity relationships • Multiple geometrical representations • Class differences
	Opportunities	**Threats**
Domain Perspective	AEC domain: • Facilitating Site Selection • Evaluation of Design Proposals • Facilitating the analysis on energy consumption and lightning requirements • Integration of logistics operations into large-scale 4D simulations • Assessment of damage (and in support renovation projects) Urban Management domain: • Facilitating 3D Modelling of Urban Environment • Facilitating Evacuation Activities • 3D geo-coding • Registration of Ownership Rights in 3D Cadastre • Public Participation • Property Tax Evaluation	• Limitations on personal privacy and anonymity • Information overload • Unauthorised access to geo-referenced building information

A frequently used integration method is to convert BIM data to geodata (one directional). Here, the standards IFC (for BIM) and CityGML (for geodata) are often used, see figure 5. Several issues have arisen during such conversions:

- complex geometric conversions: IFC uses many different types of geometries such as Swept Solid, Constructive Solid Geometry and Boundary Representation (BRep), while CityGML only uses BRep. (Isikdag and Zlatanova, 2009; Deng et al., 2016 and Liu et al., 2017).
- differences in the coordinate systems: IFC uses a local and relative coordinate system while CityGML uses a geodetic and projected one (Isikdag and

Zlatanova, 2009; Deng et al., 2016 and Liu et al., 2017). According to Noardo et al. (2020a), this could be improved if the georeferencing information is stored in a more standardised way in the IFC files and that software tools are designed to read and use this information.

- semantic information: IFC includes more semantic information than CityGML and to avoid information loss during conversion, the CityGML model need to be extended (de Laat and van Berlo, 2010; El-Mekawy et al., 2012; Deng et al., 2016 and Liu et al., 2017). It is also the other way around as CityGML contains information that is not included in IFC. IFC and CityGML are structured differently, information from one IFC object can for example fit on many different objects in CityGML.
- differences in the structures: in IFC, objects can be connected to each other in many ways and are not statically defined on the IFC schema level. In CityGML, this is defined and objects can only connect in a certain way. This causes problems during conversion (Isikdag and Zlatanova, 2009; de Laat and van Berlo, 2010 and El-Mekawy et al., 2012).
- different LOD definition: In IFC, LOD stands for Level of Development and in CityGML for Level of Detail and these two LODs do not match. This could be solved by converting the IFC geometry to CityGML LOD4 and then generalise from LOD4 to the other CityGML LODs (Deng et al., 2016).

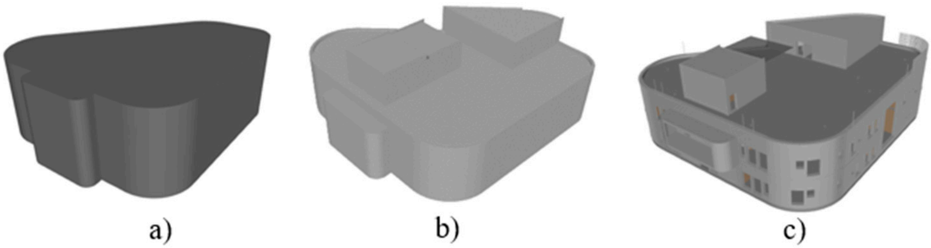

Figure 5 *Examples of a conversion of a building from IFC to CityGML using FME. a) shows the building in CityGML LOD1, b) in LOD2 and c) the original IFC model (from Eriksson et al., 2020a).*

The integration can also be bi-directional, i.e. both from BIM to geodata and vice versa. Examples of methods that are used here are: by having a reference ontology as an intermediate level between IFC and CityGML (Deng et al., 2016); and by using a unified building model (El-Mekawy et al., 2012).

Another issue when converting data from IFC to CityGML is that many geometric or topological incorrect objects exists in the IFC data, these need to be corrected before the conversion is performed (Arroyo Ohori et al., 2017).

3.3 Conformance testing

A prerequisite for a well-functioning digital information flow is that the information conform to a standard or a specification. To ensure that the information meets all defined requirements, the standard often includes an Abstract Test Suite (ATS). This is the case for both the INPSPIRE and the CityGML specifications. The purpose of the ATS is to help data providers in the conformance testing process by describing tests that datasets must pass in order to fulfil the requirements that are stated in the specification. The theme specific ATS for INSPIRE specifications was presented at the INSPIRE Conference in 2012 by Cetl et al. (2012). The principles behind conformance testing and how to add results to the metadata was described. Open issues are for example how extensions based on INSPIRE specifications should be tested. Tamash (2012) also studied the conformance testing of INSPIRE specifications and is concerned about the fuzziness between legal obligations and technical requirements in for example the specification for Administrative Units.

The validation rules in CityGML were evaluated in a quality interoperability experiment performed by OGC, the Sig3D quality group[7], and the European Association for Spatial Data Research[8] (EuroSDR), (OGC quality-ie, 2016). The aim was to give a better understanding of the requirements in CityGML and how these requirements can be validated. Geometric and semantic validations were performed, and conformance requirements were tested in a formal and automatic way. Results show that to be able to validate geometries, the number of possible geometry types must be restricted, tolerance requirements for the geometries must be added and semantics and geometry must cohere.

Another type of test is to judge the quality of a dataset based on how the dataset will be used, i.e. fitness for use. Meijer et al. (2015) developed a web-based workflow tool that help quality experts to verify the quality based on the quality elements in the standard *Geographic information — Data quality* (ISO 19157:2013). The workflow tool was tested in use cases and results show that the time for handling reports to EU had decreased and the quality of the reports had improved.

Conformance tests should also consider that standards and specification can include references to other standards. That is, the conformance test for a standard can have dependencies to the conformance test of the referred standard (Yu, 2015). Usually the conformance statements of referred standards are assumed to be true if the real value is unknown (the stub assumption, SA). This is not always the case, and Yu developed a directed dependency graph that takes into account SA, closed world assumption (CWA) and open world assumption (OWA). By using this graph,

[7] https://www.sig3d.org/index.php/en/sig3d-quality-working-group.html

[8] http://www.eurosdr.net/

inconsistencies and incompleteness can more easily be found in the referred standard.

Definition of concepts in a specification can be ambiguous and allow for many variants. The definitions are often described as recommendations, not as requirements. Such issues can be difficult to test in an ATS and can result in concepts that are described slightly different in different datasets which can hamper information exchange between these datasets. This was further examined in Paper II (Eriksson et al., 2018) where the definition of the building part concept in four standards was compared, together with their potential usage, and possible consequences of using them. One way to overcome this ambiguity of concepts is to create modelling guidelines with recommendations on how to model 3D building objects in a correct way for the intended purpose. An example of this is the guidelines by the SIG3D Quality Working Group (2017) which states for example how the LODs should be defined, which geometry types to use, and valid and invalid ways to divide a building into building parts. To ensure that data is collected or converted in a uniform manner, surveying guidelines should also be used. The Swedish surveying guidelines for Geometric representation on exchange (Svensk Geoprocess guidelines, 2018), is an example of this. The guidelines define requirements for data collection and data exchange for information that conform to the Swedish specification for buildings (Svensk Geoprocess building, 2018) and four other spatial themes. According to the guidelines, buildings can be represented in 2D or 3D and in different LODs. Different LODs have different requirements both concerning surveying methods, tolerances, and how the geometry should be represented. A practical test of developing, using and evaluating guidelines was performed as a part of the study described in Paper III (Sun et al., 2019a). Modelling guidelines was developed and then tested by constructing 3D geodata building models from both BIM models and Airborne Laser Scanning (ALS) together with footprint data using the same guidelines.

3.4 Interoperability challenges in current open standards

Open standards are often seen as the means for harmonisation and interoperability so that data can be exchanged and re-used in an efficient way. This is true both for 3D city models and BIM models, and for the emerging integration between the two, often denoted GeoBIM. The two most commonly used standards in this area are CityGML for geodata and IFC for BIM. Both standards are comprehensive, they include deep hierarchic data structures, complex relations and allow for a wide variety of object-oriented representations, and the same model can be represented in several ways and still be valid. This is a challenge for data providers, for software developers developing tools for the standards, and finally for end-users using these tools.

The GeoBIM benchmark project, funded by the International Society for Photogrammetry and Remote Sensing[9] (ISPRS) and EuroSDR, investigate these issues further. The aim of this project was to examine the software support for IFC and CityGML and the conversions between the two standards. Two major technical issues related to GeoBIM integration, the ability of tools and methods to georeference IFC, and the conversion procedures between IFC and CityGML were also tested. The benchmark tests were performed by volunteers from different fields and there were no expertise nor skill requirements to participate.

Interoperability within a standard, that is GIS-to-GIS and BIM-to-BIM, imply that a dataset should remain unchanged when going through imports and exports by software tools. Results from the task studying software support for CityGML show that this is not always the case (Noardo et al., 2020c). 15 software packages, including both CityGML viewers and generic GIS tools, were evaluated, and many tools did not support the features or functionalities in CityGML accurately. The software tools could also misinterpret data structures, e.g. geometry, semantics and georeferencing in these standards.

The task that studied software support for IFC shows similar results (Noardo et al., 2020b). IFC includes deep hierarchical data structures, complex part-of hierarchies, subtraction relationships (i.e. openings) and can associate objects in various combinations. Also geometries in IFC can be described in different ways. 31 software packages were tested and many tools had difficulties to interpret the semantics correctly, to support georeferencing and to correctly export the dataset without losing or adding objects. The support for visualisation of geometries were better though.

Conclusions from the software tool tests for CityGML and IFC are that very few tools could read the standardised datasets correctly and even fewer could export them consistently. This creates a gap between end-user expectations and what the tools can accomplish. For CityGML, Noardo et al. (2020c) propose to simplify complex hierarchies and relations, to have clear definitions of entity structures, to constrain the validity rules for geometries, and to reduce the size of the GML files. Improvements to IFC could, according to Noardo et al. (2020b), for example be to add constraints, have simpler ways of storing the geometry, include a better selection of useful semantics, to create open source libraries to read/write IFC and develop specific guidelines.

An effect of the interoperability issues within the CityGML and IFC standards is that the interoperability between standards, that is BIM-to-GIS (IFC to CityGML) or GIS-to-BIM (CityGML to IFC) will be even more difficult to accomplish (Noardo et al., 2020b). If software designed for IFC cannot consistently read and write IFC it will be almost impossible for conversion software to correctly convert

[9] https://www.isprs.org/

and write it in CityGML format. The GeoBIM benchmark project performed both IFC to CityGML and CityGML to IFC conversions (Noardo et al., 2020a). The most commonly used software were FME from Safe Software, either directly or as a plugin to ArcGIS from Esri[10]. The converted models were analysed in 3D viewers to check the geometry and semantics, manually to check consistency and correctness and in automatic validation tools. Conversion from IFC to CityGML is the most commonly used method. The same conversion issues as described in section 3.2 were also encountered here, such as difficulties to convert certain geometries, and where the standards diverge, for example concerning semantics and georeferencing. As IFC generally has more fine-grained details than CityGML, conversion from CityGML to IFC is generally more difficult. It is also important to have sufficient knowledge of IFC, CityGML and of the conversion tool to be able to develop a well-functioning conversion method.

The open standards themselves can contribute to the issues described above as they allow for a variety of complex representations and leave certain details undefined, allowing for different interpretations. One possible reason for this is that open standards can be the result of a merger of existing best practices and compromises between relevant stakeholders. The best way to overcome this would, according to Noardo et al. (2020c), be a collaboration between software developers and standardisation organisations with a main focus on the requirements from the users.

3.5 Lifecycle and versioning management

Lifecycle and versioning management is another important prerequisites for a continuous information flow in the planning and building process. The term lifecycle can be used in a data handling context, for example for planning, collecting, storing and publishing data. Another usage of the term comes from the product management domain and is often referred to as product life cycle (PLC). It describes data for supporting the production process so that data are transferable between the design, construction and maintenance phases of a product. This way of modelling lifecycle data has become increasingly common also in the BIM domain and it also affects geodata in those cases where BIM data and geodata are integrated.

The sections below describe methods that are commonly used to describe lifecycle information in different sectors and for different purposes.

[10] https://www.esri.com/en-us/arcgis/about-arcgis/overview

3.5.1 Data Lifecycle Management

Already in 1993 Levitin and Redman defined a data lifecycle. It relates to the product lifecycle and includes four cycles that are related: acquisition, usage, "store-and-forward" and "information storage and retrieval". Levitin and Redman also state the importance of having quality checks of the data and feedback loops. During the last decades, the use of Big Data (often described as volumes of data that are too large or complex to be dealt with by traditional data-processing software) has increased, and has also put new requirements on data lifecycle management, for example to extract relevant information from the data. That is, intelligent processing of the data should transform the initially unstructured data into knowledge, and this transforms Big data into Smart data (Lenk et al., 2015). El Arass et al. (2017) performed an analysis of 12 data lifecycle models based on eight criteria: Adaptation to Big Data, Security, Supervision, Management, Quality Control, Green, Intelligence level, and Flexibility of the cycle. Results show that no model fulfilled all requirements, and that different models should be used for different purposes. With this as a background El Arass and Souissi (2018) propose a new data lifecycle model for Big Data called Smart Data Lifecycle (Smart DLC). They describe the phases in Smart DLC as processes according to the Quality management systems – Requirements standard (ISO 9001:2015) and the CIGREF framework[11]. Three process types for transforming Big Data into Smart data are defined: Management, Realisation and Support, which in turn comprise of processes (Figure 6). The use of standards and the inclusion of process and task descriptions will, according to El Arass and Souissi, result in a better data lifecycle management support concerning cost, quality and time.

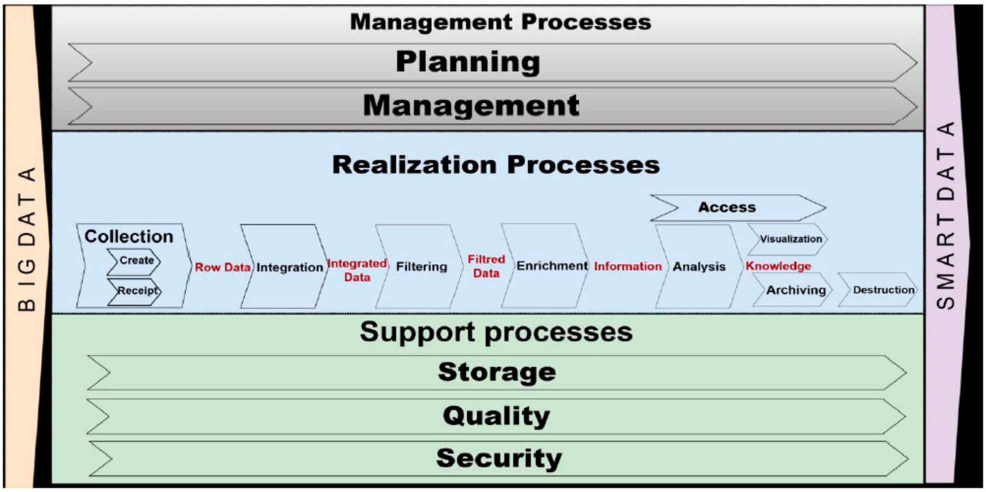

Figure 6 *Smart Data Lifecycle (from El Arass and Souissi, 2018)*

[11] https://www.cigref.fr/english

3.5.2 Product Lifecycle Management in the manufacturing sector

In the manufacturing sector, Product Lifecycle Management (PLM) has been used for many years to provide the right information about a product at the right time and in the right context. Stark (2015) describe the PLM Initiative that includes five pillars of PLM: business processes; product data; information systems; organisational change management and project management. According to Stark, all pillars must be taken into consideration when wanting to improve the product-related performance of a company and to improve the management of products across their lifecycles.

Terzi et al. (2010) describe that an issue with PLM is that it focuses on the first phase of the product (design and manufacturing), but almost no product information is transferred to the middle and end phases (distribution, use, support, recycling and disposal). Using PLM in these phases would give feedback from customers to designers and provide maintenance and recycle operators with up-to-date product information. Vadoudi et al. (2014) also state the importance of handling product information in later phases of the product life cycle, as this is a prerequisite for a sustainable product lifecycle management, where environmental issues play an important role.

The manufacturing process often includes both Product Data Management systems and the Enterprise Resource Planning systems which have semantic differences in how a product is described. This can cause interoperability issue in PLM, which in turn makes it difficult to create a global description of the whole product development process (Paviot et al., 2011). The authors see the Product Lifecycle Support standard (PLCS; ISO 10303-239:2012) as a possible mean to overcome these semantic interoperability issues.

3.5.3 Lifecycle management in the planning, building and construction sector

Also the planning, building and construction sector needs lifecycle management to for example overcome ineffectiveness in the construction life cycle. Owen (2009) propose a holistic vision, the Integrated Design & Delivery Solutions, that contains four key topics that must be examined and treated together for the vision to come through. The topics are Collaborative processes; Integrated information and automation systems; Enhanced skills; and Knowledge management.

Hallberg and Tarandi, (2011) describe the need for a detailed long-term plan for maintenance, repair and rehabilitation to make more effective use of resources. This could be achieved by a Lifecycle Management System (LMS), which is a further development of facility management (FM). LMS includes modules for Inventory registration, Condition survey, Service life performance analysis, Maintenance analysis, Maintenance optimisation and Maintenance-Planning. LMS also makes it possible to predict and optimise future maintenance activities. Hallberg and Tarandi propose to use open BIM, i.e. BIM together with open standards such as IFC and PLCS, to facilitate the implementation of LMS, as open BIM makes the information accessible and readable by anyone and can thereby be more easily used by all FM applications.

A general question in the lifecycle management of data is whether it would be possible for actors in earlier phases of the process to create e.g. a BIM model suitable also for later stages. Kiviniemi and Codinhoto (2014) describes that even though BIM is successfully used in the design and construction processes, BIM is rarely used in facility FM activities. This can be both because BIM in the construction phases does not include all information needed in FM; and due to organisational issues, such as cultural barriers and the lack of legal frameworks.

3.5.4 Lifecycle management of 3D city models and 3D buildings

More advanced use of 3D city models requires for example that they are linked to other registers and models. This in turn requires that the 3D city models are continuously updated, that is, they need lifecycle management.

When focusing on the different objects (e.g. buildings, roads and bridges) in a 3D city model, one can see that the digital representation these objects are evolving in parallel with the physical real-world objects. Taking buildings as an example, during the different phases, the AEC companies will continuously develop and update a BIM model; from an initially simple architectural model to a gradually more advanced BIM model. In several phases, this model is passed to other actors, and some actors, such as municipalities, are more interested in a comprehensive geodata description of the building. That is, throughout the process there will be two parallel descriptions of the building, a BIM description and a geodata description. However, to achieve a process-oriented digital information flow, it is important that the buildings are treated as the same real-world objects through their whole lifecycle, with information that evolve over time and that can be described with different attributes and geometries either as BIM or as geodata (Figure 7). This in turn presupposes that both the BIM and the geodata models are versioned.

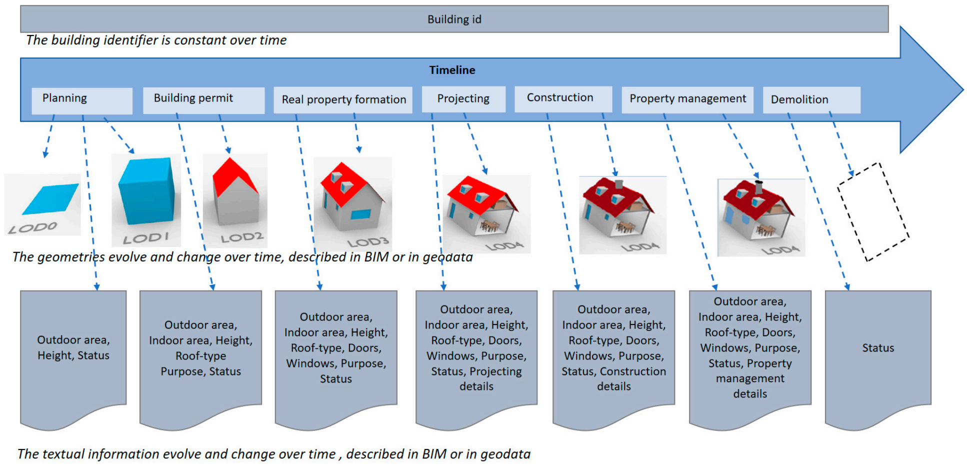

Figure 7 *The lifecycle of a building (building figures from Biljecki et al., 2014 with LOD descriptions according to CityGML 2.0)*

The spatio-temporal information in a 3D city model can be described in various ways. Chaturvedi and Kolbe (2019) distinguish between *quantitative changes* that describes functions of time on an object, such as energy consumption for a building that vary over time, and *qualitative changes* where objects are created and disappear over time, such as the constructing and demolition of a building. 3D city models should handle both types of changes and Chaturvedi and Kolbe define seven requirements on how 3D city models should be extended with additional temporal and dynamic properties to accomplish this: 1) *Linking sensors and IoT with city objects* – seamless integration of sensors and IoT devices into the 3D city model, 2) *Events and alerts* – enabling automatic notification on desired information, e.g. for flooding, 3) *Moving objects* – connections between city objects and moving objects, e.g. mobile measurements from a car, 4) *Supporting timeseries in-line within city objects* – adding time-dynamic properties to city objects, e.g. energy demand estimations for buildings, 5) *Supporting complex patterns and schedules* – add patterns based on statistics and general rules to an object, 6) *Managing alternative versions* – have different planning versions of city objects, e.g. urban planning scenarios, and 7) *Managing historic versions* – have multiple representation of the past of a city and handle different historical versions of the model.

During the last years, lifecycle and version management methods for 3D city models and 3D buildings have started to emerge, and existing standards for 3D city models include functionalities to fulfil at least part of the requirements mentioned above. Chaturvedi and Kolbe (2019) evaluated three 3D city models (IFC 4, INSPIRE and CityGML 2.0) against these requirements. Results show that none of the models have complete support for all requirements, but they all have limited support for some. Three CityGML ADEs were also tested, the Energy, Dynamizer and

Versioning ADEs and they all had complete support of the requirements within their fields. Finally this was compared to the functionalities in the proposed version 3.0 of CityGML. Here the Dynamizer and Versioning ADEs are included as two new modules which extends the support in CityGML for these areas.

The sections below describes temporal modelling of geodata in general, versioning methods for CityGML and CityJSON and also how the PLCS standard and a graph database could be used for change detection and versioning of 3D city models.

3.5.4.1 Temporal modelling of geodata

Lifecycle information in spatio-temporal information systems can be organised in many ways. Worboys and Duckham (2004) defined four stages: *static representation* for representation of single moment in time, the *snapshot metaphor* for temporal snapshots of a state at a certain time, *object lifelines* for changes of state over time for objects, attributes and their relations, and *events, actions and processes* where continuants (things that endure through time) and occurrents (things that happens and then are gone) are described. Worboys (2005) describes another view where geographic phenomenon are described in an event-oriented way that can serve the increasing demand for geographic information in various planning and prediction making processes. Here, time is defined as a collection of separate tick events ordered as sets of channels that is referenced to as a clock.

Geodata that includes temporal information can be stored in spatio-temporal databases where changes over time in the geometry, attributes or topology of objects are captured and can be queried. Two types of time representations are often used: *transaction time* that defines when changes occur to objects in the database (create, update or remove), and *valid time* that reflects the time when things happens in reality (e.g. when a building received a building permit). In some cases, datasets include both transaction time and valid time, this is denoted bi-temporal modelling. It is possible to have these timestamps on different levels. Taking buildings as an example, the timestamp could be on the entire building, on building parts, on the geometry or even on individual attributes. The more detailed levels that are timestamped, the more storage capacity will be required, but temporal changes can also be traced at a finer granularity (Wieland and Pittore, 2017).

3.5.4.2 Versioning in CityGML

The inclusion of temporal information and versioning methods in 3D city model standards is evolving. CityGML 2.0 includes the attributes *creationDate - terminationDate* which represent the transaction time, and the attributes *yearOfConstruction* and *yearOfDemolition* of a building. CityGML 3.0 also includes *creationDate – terminationDate* and has refined the attributes for certain moments in time for the building: *dateOfRenovation* is added and the data type for *dateOfConstruction*, and *dateOfDemolition* is changed from *Year* to *Date* format. In CityGML 2.0 these attributes belong to the *AbstractBuilding* feature, and in

CityGML 3.0 to the *AbstractConstruction* feature. Both *Building* and *BuildingPart* inherits from these features, therefore those dates can be set on both buildings and building parts (figure 8).

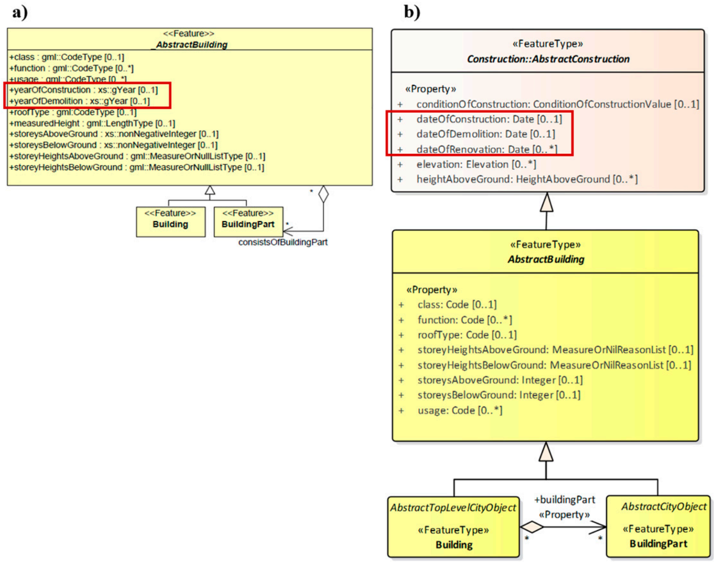

Figure 8 *Temporal attributes in a) CityGML 2.0 (from Gröger et al. 2012) and b) CityGML 3.0*

The attributes *validTo* - *validFrom* referring to the lifespan of a real-world object is also added. CityGML 3.0 further includes a new versioning module that contains the feature types *Version*, *VersionTransition* and *Transaction* which makes it possible to have different versions of the 3D city model and to define which objects that belong to a certain version, see figure 9 (Chaturvedi et al. 2016). Links between different versions of the 3D city model is created using *VersionTransition*, where reasons for change can be described. The feature type *Transaction* describes the transactions (insert, delete or replace) included in a certain *VersionTransition*. Versions are also allowed to fork in order to e.g. represent alternative plans of a city.

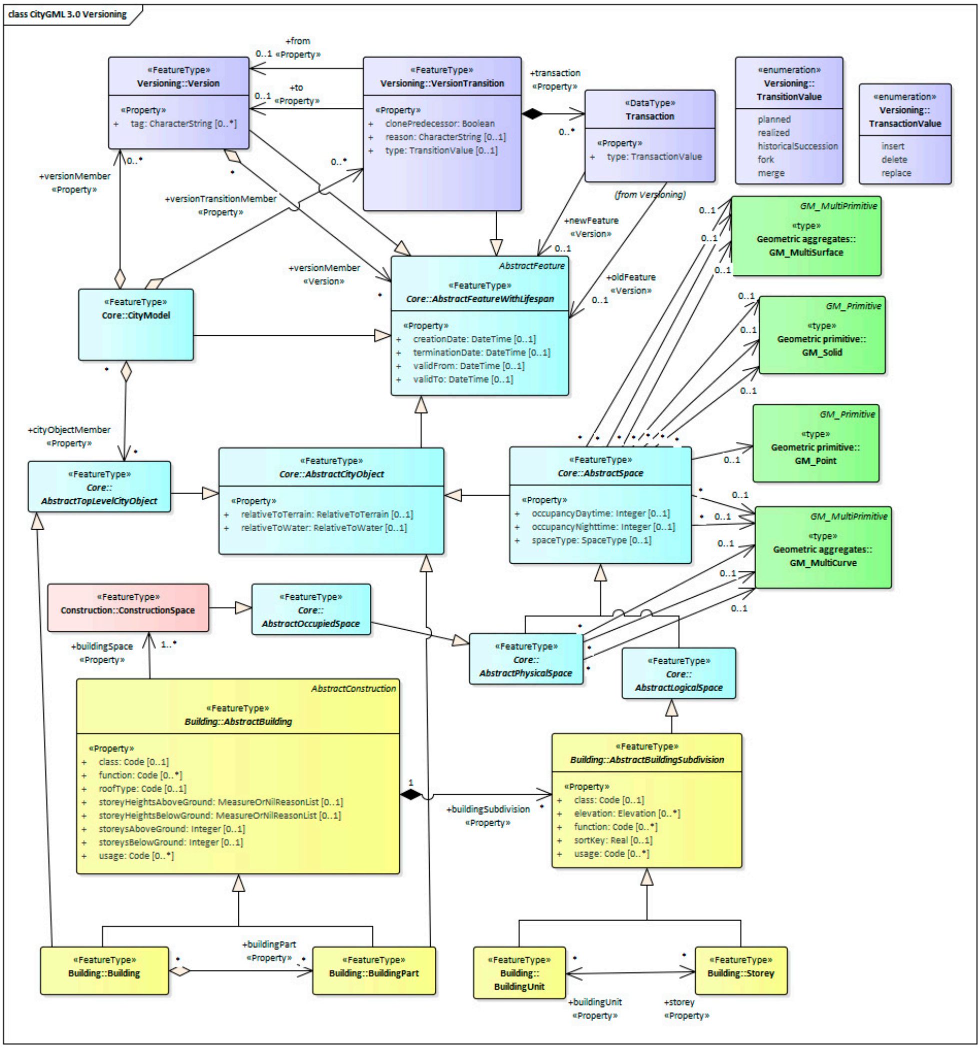

Figure 9 *Selected parts from CityGML 3.0, the versioning module in purple*

3.5.4.3 Versioning in INSPIRE Building

Some attributes are included in all INSPIRE themes, for example the temporal attributes that describe the lifespan for database transactions: *beginLifespanVersion* and *endLifespanVersion*. In addition to these attributes, the building theme also includes attributes that specifies certain stages for the building: *dateOfConstruction*, *dateOfRenovation* and *dateOfDemolition*, and a versioning identifier, *versionId*.

3.5.4.4 Versioning in CityJSON

CityJSON does not include any versioning information, but Vitalis et al. (2019) developed a modified Git versioning method that was implemented in CityJSON. This method has a data structure similar to the DAG (directed acyclic graph) structure in Git, a version control system mainly used for computer programming. The DAG consists of nodes that represent objects or data, and directed edges representing relationships between them. All nodes know their parent so the graph can be traversed from leaves to the root. All city objects are listed as *CityObjects* properties and all versions are listed as *versioning* properties. A *version* includes the building objects that belongs to this version together with a *date* property that defines the date of a version in the CityJSON model, a *parents* property that links to the previous version, and a *message* property (figure 10).

a)

```
"CityObjects": {
    "BU-01": {
    "type": "Building",
    "attributes": {
        "storeysAboveGround": 1,
        "storeysBelowGround": 0,
        "function": "residential building"
        }
    }
    "BU-01-Renovated": {
    "type": "Building",
    "attributes": {
        "storeysAboveGround": 2,
        "storeysBelowGround": 0,
        "function": "residential building"
        }
    }
}
```

b)

```
"versioning": {
    "versions": {
        "ver-01": {
            "author": "City Official"
            "date": "2007-12-17"
            "message": "Construction completed"
            "objects": ["BU-01"]
        }
        "ver-02": {
            "author": "City Official"
            "date": "2020-05-23"
            "message": "Building renovated"
            "parents": ["ver-01"]
            "objects": ["BU-01-Renovated"]
        }
    }
}
```

Figure 10 *Example of the modified Git versioning proposal,* ***a)*** *city objects listed under the CityObjects property and* ***b)*** *versions are listed under the versioning property*

3.5.4.5 Product Lifecycle Support standard

The PLCS standard (ISO 10303-239:2012) was originally developed for the process and manufacturing industry and has mainly been used to support complex products such as planes and ships. It includes information required for through life configuration and change management of a product, and supports a seamless flow of information from the design and manufacturing to the phases for product support and change. The PLCS standard can for example represent: product structures, assemblies and breakdowns; product through life; specification and planning of activities; and product history.

PLCS has also been used for the lifecycle management of BIM models. Tarandi (2015) developed the BIM Collaboration Hub, a prototype platform that makes it possible to store BIM information that is created using different software and in different phases of the construction process in the same place. It is based on the PLCS standard and to this, BIM data conforming to the IFC standard is mapped.

The information is accessible by anyone and can facilitate the creation of a detailed long-term plan for maintenance, repair and rehabilitation. This makes information more easily available also in later stages, for example for facility management. Within a testbed project[12] this was taken one step further by storing both BIM and geodata models in a data collaboration environment called ShareAspace[13]. This makes it possible to synchronise the versioning of BIM and geodata models that represent the same real-world building, and also to have different intermediate versions in BIM and geodata of the same building. This is described in Paper V (Eriksson et al., 2020b) where the use of PLCS as a versioning method for 3D geodata buildings is compared with using the new versioning capabilities in CityGML 3.0 (Chaturvedi et al. 2016) and the modified Git versioning proposal implemented in CityJSON (Vitalis et al., 2019).

3.5.4.6 Spatio-semantic comparison of CityGML models

Another way of detecting changes in a 3D city model is to use a graph database to detect spatio-temporal changes on CityGML datasets. Nguyen et al. (2017) propose such solution and argue that this is an advantage as changes can be difficult to detect in CityGML models due to their complex structures and sematic properties. Nguyen et al. found graphs to be a suitable choice as CityGML resembles a graph structure due to the inclusion of XLinks, which makes it possible for an object to have multiple parents. Nguyen et al. implement their graph database in neo4j[14], an open-source, NoSQL, native graph database where objects are stored as *nodes* and relations between objects as *edges*. The major steps of using a graph database to detect changes in a CityGML dataset is to map, match and update. An old and a new CityGML dataset were mapped to graph entities in neo4j. The node properties and geometries of the two resulting graphs were then matched. All changes that were made to the old CityGML dataset in the test case were found and the old dataset was then updated with these changes using a Web Feature Service.

Nguyen and Kolbe (2020) extended the above graph database proposal to also include user-oriented interpretation of the detected changes, as different users and stakeholders can have different interests and expectations on changes of the 3D city models. For example developers are interested in all detected changes of the model, while surveyors are interested in how 3D city models can be continuously updated, and city administrators are interested in the progress, such as how many buildings that have changed and what the most frequent changes are. Nguyen and Kolbe therefore propose an enhanced mapping and matching process of CityGML datasets. The changes detected when matching the graphs are divided into different edit

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[12] https://www.smartbuilt.se/projekt/innovationer-och-nya-tillaempningar/testbaedd/#

[13] https://www.eurostep.com/products/shareaspace/

[14] https://neo4j.com/neo4j-graph-database/

operations and the changes are categorized based on the sematic content: procedural, thematic, syntactic, geometric, structural and top-level (figure 11).

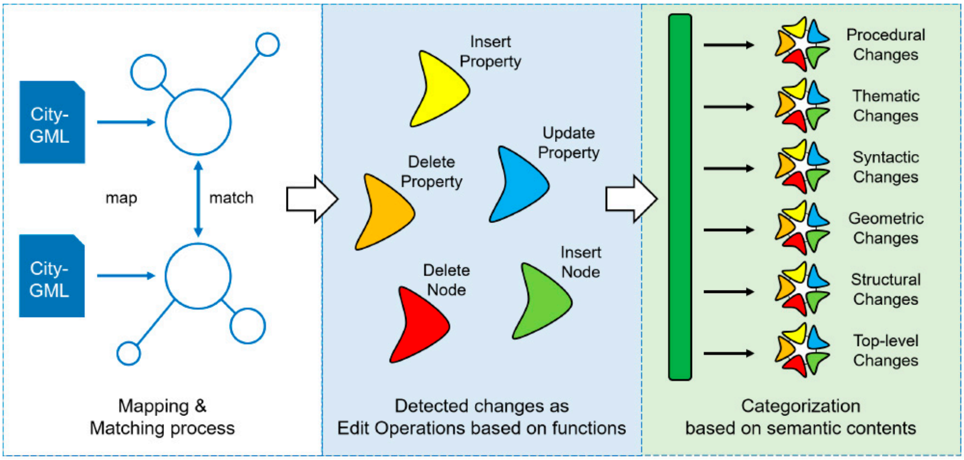

Figure 11 *An overview of the process described by Nguyen et al., (2017), with extended mapping and matching to better produce edit operations from detected changes. (from Nguyen and Kolbe, 2020)*

4 Summary of papers

Harmonisation of geographic data is a broad area that includes technical, organizational, legal and educational issues. This thesis concentrated on technical aspects for the harmonisation of geographic data. Figure 12 shows how the studies relate, and highlights different aspects of the data harmonisation.

Standards for geographic data often focus primarily on one geographic level. Examples of this are: the INSPIRE directive with the main focus on cross-border applications at a European level; and the Swedish water system standard that has a national focus. That is, there is no harmonisation between the geographic levels. If harmonisation can be improved by extended the INSPIRE specification for hydrography with all additional information in the Swedish water system standard is evaluated in my first paper (number I in figure 12). An observation during the study of hydrography specifications was that there are a number of concepts that are defined in a similar but not identical way in the specifications. This can affect the harmonisation of data, especially if the concepts concern hierarchic manmade structures such as building parts. How this can affect data harmonisation is evaluated in the second paper (II). One possible way to come around the problem with similar definitions could be to create national guidelines on how a concept should be used in a national context. The creation and usage of guidelines is evaluated in the third paper (III), as part of a study performed by Sun et al. (2019a). The importance of using standards and guidelines and the need to coordinate these, for example at national level, are conclusions that can be drawn from the previous studies. Another conclusion is the importance of gathering and evaluating user requirements before a new standard or specification is developed. These were all taken into account in the fourth paper (IV) where a proposal for a Swedish building standard were developed and evaluated. The evaluation of requirements for 3D city models that was conducted in paper four revealed a trend for more complex 3D city models that requires city models to be continuously updated and versioned. In the fifth paper (V), three different versioning methods that can be used for versioning of 3D city models were examined and evaluated. Even though versioning methods for 3D city models exist, they are rarely used. In the sixth paper (VI) issues that must be solved for these versioning methods to be used in practice are studied and recommendations on how to overcome this is proposed.

The sections below summarise the papers included in this thesis.

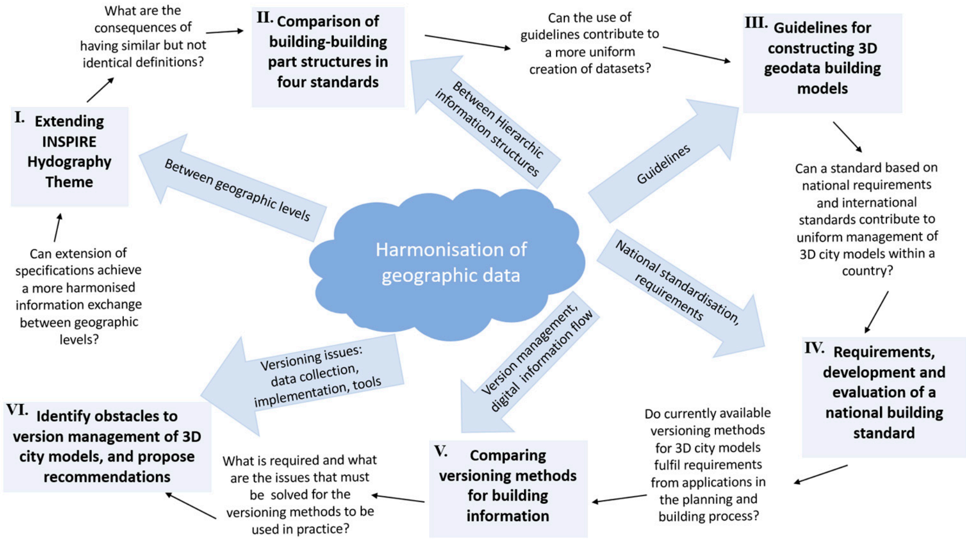

Figure 12 *Overview of the papers in this thesis*

4.1 Paper I

The aim of this paper is to create a formal extensions of the INSPIRE specification for hydrography to evaluate if it is possible to create a complex INSPIRE extension and what the consequences of using an extended INSPIRE dataset are, from the perspectives of both users and data providers.

A standard for geographic data often focuses primarily on a certain geographic level. Examples of this are the specifications for the 34 geographic themes included in the INSPIRE directive (Directive 2007/2/EC, 2007). The main focus is to enable the sharing of spatial information for cross-border environmental applications at a European level. A standard can also have a national focus, such as the Swedish water system standard (SWSS; SS 637008:2015, 2015), that includes detailed hydrographic information that is of interest from a Swedish perspective. In addition to this, Sweden has a regional data specification for water that serves municipal needs (Svensk geoprocess water, 2017). A consequence of having different specifications for different geographic levels is that this results in one dataset per specification and a view and a download service each for providing the information. An effect of this from a user perspective is the need to use three different datasets depending on the application; and from a data providers perspective, the need to produce three different datasets and corresponding view and download services to provide the information. That is, the information is not harmonised between the geographic levels.

This paper concentrates on harmonisation between geographic levels by extending the INSPIRE specification for hydrography, HY (INSPIRE Hydrography, 2014) with all additional information in the Swedish water system standard. Examples from literature show that it in many cases are preferable to extend a specification with additional information instead of creating a new specification from scratch, but no articles that describes very complex extensions was found. Requirements and examples of how to extend INSPIRE specifications can be found in the INSPIRE GCM (INSPIRE Generic Conceptual Model, 2014). Recommendations and design patterns on how such extensions can be implemented was developed by for example Wetransform[15], and have been used in this study.

The usability of the resulting dataset is also important to consider. It was not possible to find any similar evaluations in literature and we therefore decided to perform our evaluation both from the perspective of users and from data providers. This was carried out using: a quantitative test of the resulting GML files; in a test where a user uses and compares GML files from three sources (INSPIRE HY, SWSS, and extended INSPIRE HY) in hydrological analyses; and by semi-structured telephone interviews with personnel from the data producer Lantmäteriet[16]. The results show that it is possible to include all information needed at regional- national- and European level in the same specification and to develop that as a formal INSPIRE extension. Advantages are that by doing this, the number datasets and services for providing the information will be reduced. The format will also be the same for all levels, that is, information does not have to be converted between levels. Disadvantages are that this results in a comprehensive and complex standard that can be difficult to implement, and the national standard will be dependent on changes in INSPIRE. Some user groups might also prefer to have a dataset that is tailored to their specific needs instead of having a dataset that includes all hydrographic information.

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[15] http://inspire-extensions.wetransform.to/extension-methodology.html

[16] The Swedish mapping, cadastral and land registration authority, https://www.lantmateriet.se/en/

4.2 Paper II

The aim of this paper is to study how building parts are defined in various specifications, to describe potential use of building parts, and the consequences of using them.

A number of concepts are defined in a similar but not identical way in related specifications. This can affect the harmonisation of data, especially if the concepts concern hierarchic manmade structures such as building parts. There are various ways of dividing a building into smaller parts and how this is done is somewhat different between standards. This paper first studies the definition of building parts in the geodata specifications CityGML 2.0 (Gröger et al., 2012), INSPIRE Building (2013) and in Svensk geoprocess Building, a Swedish geodata standard (Svensk geoprocess building, 2018); and in the and building information modelling (BIM) standard IFC (ISO 16739:2013, 2013). Thereafter, potential applications for the use of building parts, on what grounds a building could be divided into building parts, advantages and disadvantages of having building parts, and what consequences it can have on the usage of the building information are described.

The building part concept is described in a similar, but not identical way in the four standards, both concerning the usage and how the structure can be constructed. For example, in CityGML it is allowed to have structures of both building - building part and of building part - building part. In INSPIRE Building it is only possible to have building - building part structures, which is also the case for Svensk geoprocess Building, but with the main difference that here, the geometry is only defined on the building parts, not on the building itself. That is, all buildings with a geometry must consist of at least one building part.

There are several reasons for why a building can be divided into building parts, it can be due to: physical aspects (such as height above ground and roof type); functional aspect (for example current use); and temporal aspect (year of construction). These are all recommendations though, no requirements on when buildings must be divided into building parts exist. Therefore, the division is arbitrary and it is not clear when to use what. This in turn can in some cases complicate the modelling, exchange and reuse of building information in applications such as building permit management, 3D property formation, visualisation, and in the conversion process from BIM to geodata buildings. An example is when a BIM model is used as the source for a 3D geodata building, the structure of the geodata model will probably have the same hierarchic structure as the BIM model, including the division into building parts, but this might not be the way the geodata community (e.g. municipalities) prefer. One possible way to improve and simplify this is to create national guidelines on how to use building parts in a national context.

4.3 Paper III

The creation and usage of guidelines was tested and evaluated in Paper III, as part of a study performed by Sun et al. (2019a). The aim of this study was to evaluate BIM as a source for updating city models in level of detail (LOD) 1 and 2 of CityGML, and to compare this with the use of Airborne Laser Scanning (ALS) and footprint data. The integration of BIM into city models was formalized by creating modelling guidelines for constructing the 3D geodata building models and then developing routines for creating CityGML LOD1 and LOD2 building models from BIM based on these guidelines. Methodologies for creating CityGML LOD1 and LOD2 building models from ALS and footprint data were also developed. For comparison reasons, the two methodologies were based on the same guidelines. Finally, the geometric aspects of the resulting CityGML building models were compared and evaluated visually and quantitatively.

My part in this study was to create the modelling guidelines. One person used the guidelines for creating CityGML buildings from BIM and another person for creating CityGML buildings from ALS and footprint data. The study demonstrated that the same modelling guidelines could be used to describe routines for extracting CityGML data both from BIM and ALS/footprint data and that these routines provide models that are visually and quantitatively similar, enabling them to be used together in a production environment. One lesson learnt though is that formulating simple but sufficiently comprehensive modelling guidelines for deriving CityGML buildings from both ALS/footprint data and from BIM, in a way that all users interpret them the same way, is challenging. Some unclear formulations were found during a review of the first version, and the guidelines were updated. However, some of the differences in the resulting models are still due to different interpretations of the guidelines and it is therefore important to test the guidelines under real conditions before they are used in a production environment.

4.4 Paper IV

The aim of this paper was to develop and evaluate a proposal for a national building standard in Sweden.

Many cities around the world have developed their own 3D city models but many of those do not live up to the user expectations (Julin et al., 2018; Kang 2018). In Sweden there was a need to develop a new standard for buildings as new requirements from the planning and building process have emerged. This should be a national standard that takes all user requirements into consideration before developing the standard. This paper describes the process and present a proposal for the new Swedish building standard, CityGML Sve-Test. The standard should support development of 3D city models, connections to BIM models and national registers, be based on a national classification system for the urban environment and support the planning and building process, such as building permit handling and 3D property formation.

CityGML Sve-Test was developed as an Application Domain Extension (ADE) of the building model of CityGML within a Swedish project that was coordinated by Lantmäteriet, and that also included experts from academia, some larger cities and technical consultants (see Olsson et al., 2019). The new proposed version 3.0 of CityGML (Kutzner and Kolbe, 2018; Kutzner et al., 2020) was chosen as it includes new features that are of interest from a Swedish perspective. For example, the new space concept distinguishes between physical and logical spaces, where the logical spaces could represent the legal spaces of the 3D cadastre; and the enhanced possibilities to more easily convert data and to link to other standards such as IFC and LADM (ISO 19152:2012, 2012). CityGML Sve-Test also includes the Swedish classification system CoClass (2016) both to improve the definition of terms and to facilitate interoperability with other urban processes.

Test cases were performed to evaluate CityGML Sve-Test and the results show that it is possible to convert an IFC model to a CityGML Sve-Test dataset and that the use of CoClass can facilitate this conversion. It was demonstrated that a CityGML Sve-Test dataset can be used to automatically check if a building conforms to the regulations in a detailed development plan. It was also possible to import and visualize CityGML Sve-Test datasets in the commercial software S-Visualizer and Revit. Finally, Sun et al. (2019b) showed in a related study that CityGML 3.0 has the capability to link to legal information in the LADM standard, that cadastral information can be visualized using CityGML 3.0, and that it can be used as a base for a 3D cadastral index map.

To conclude, it is important to specify what buildings and 3D city should be used for and how complex they should be, and then settle on a reasonable level. The 3D city model, or at least its data model, should conform to an international standard, e.g., CityGML. The exchange format (XML/GML, JSON, RDF, etc.) might change in the future but to build on a well-established and standardised data model will ensure that the models both have a harmonised structure and harmonised concepts. If a classification system exists, it should be included in the standard to improve definition of terms and to facilitate the interoperability with BIM. The standard should also include lifecycle management and be complemented with measuring guidelines to ensure a more conform creation of the objects included in the standard.

4.5 Paper V

The aim of this paper was to compare and evaluate three version management methods for 3D city models.

There is a growing trend for 3D city models to be used for more than visualisation, for example for urban planning, decision making, analyses, and also to replace the 2D base maps in urban areas. This requires that the city models have connections to for example cadastral registers, which in turn requires that the city models are continuously updated and versioned. This paper examines and evaluates three different versioning methods that can be used for versioning of 3D city models in the planning and building process: the PLCS standard (ISO 10303-239:2012), the versioning module in CityGML 3.0 (Kutzner and Kolbe, 2018, Kutzner et al., 2020), and a modified Git versioning method implemented in CityJSON (Vitalis et al. 2019).

Version management is one of the prerequisites for a digital information flow in the planning and building process as the information will evolve and be used for multiple purposes and by different actors during its lifecycle. This paper focuses on the information flow in the 3D cadastre process, and a number of requirements on the version management for the 3D cadastre process were identified. Out of these, three requirements were chosen for the comparison of versioning methods: 1) Retrieve information from a specific moment in time about objects in a city model (transaction time) and about real-world objects (valid time); 2) Have different simultaneous alternative descriptions of a city model; and 3) Keep track of the synchronization of building information between BIM and geodata models.

The results show that PLCS fulfils all requirements and CityGML 3.0 meets all but one. The modified Git versioning proposal do not include dates for real-world objects, it only handles the versioning of city objects in a city model. Therefore, it did not fulfil the requirement to retrieve building information from a specific moment in time for a real-world building. This is included in the CityGML 3.0 versioning proposal, but here the geometry of a building cannot be versioned separately, which is not possible in the Git proposal either. The evaluated methods vary in complexity from the modified Git proposal that is deliberately a simple versioning method for 3D city models, to the CityGML 3.0 versioning module that is a bit more complex, to PLCS that is a very comprehensive lifecycle standard. All methods have their advantages and disadvantages, the modified Git versioning proposal is simple and easy to implement and use, but must be complemented with other methods if more sophisticated lifecycle management is needed. PLCS on the other hand includes "all" functionalities and all the lifecycle management can be performed within the same system, but PLCS can be difficult both to implement and to use. Therefore it is important to evaluate what the purpose of the lifecycle management is before selecting a method.

4.6 Paper VI

The aim of this paper is to identify obstacles to version management of 3D city models, and to propose recommendations on how to overcome these obstacles. One specific aim is to investigate if a national building register can be used to control the version management of 3D city models, and if so which requirements must be set on the specification for the national building register.

In a recent study by Vitalis et al. (2019) it is shown that a majority of openly available 3D city models are never changed, and for the ones that are, the models were often recreated instead of updated. This contrasts with the need for versioning of 3D city models that emerged in the study by Eriksson et al. (2020b). There could be many reasons for why this is the case, and Paper VI describes a study where the following six issues are examined: 1) Data provider incentives, 2) Collection of versioning information 3) Database implementation on building theme layer, 4) Capability of versioning management in the building register, 5) Mapping versioning information between layers, and 6) Application tools for 3D city models. For issues one and two surveys were sent out to a limited group of municipalities. Issues three, four and five have been studied in the context of 3D city models for Swedish municipalities, with a special focus on building information, using the proposed Swedish national specification for building information, NS building, (Nationell Informationsspecifikation Byggnad, 2019) as an example. Finally a limited review of software tools was performed to answer issue six.

The study is built around an architectural model divided into four layers (data collection, building theme, city model and application layer). All layers require changes when implementing a new versioning method. The data collection layer requires restructuring of technical solutions and work processes. The new information that should be collected is stored in other systems, provided by other software vendors, and handled by other departments in the municipalities. The building theme layer includes the national building register at the national mapping authority, NMA. This register must be restructured in accordance with NS building. The versioning capabilities must be propagated from the building theme layer to the city model layer and tools at the application layer must become better at handling standardised 3D city models and temporal information.

A conclusion is that strong incentives for including versioning in 3D city models are essential as both municipalities and the NMA must make substantial investments to implement the new versioning method. Application requirements should guide the process and only required capabilities should be implemented, as the complexity grows with the number of versioning functionalities included. One recommendation is to link the city models closer to the national building registers as it both enables more complex use of the models, and the ability for authorities to fetch required (versioning) information directly from the city model layer.

5 Conclusions and outlook

5.1 Conclusions

Harmonisation of geographic data is a broad topic and different aspects such as technical, organisational, legal, business and educational, should be evaluated to cover it all. The main focus in this thesis is on the technical aspects, and especially on a digital information flow of 3D geodata in the planning and building sector. Here, the harmonisation of geographic data between geographic levels, between hierarchic structures, and over time is studied.

Information within the planning and building process is currently often shared in non-machine-readable formats, such as on paper or as pdf files. Much would be gained if the work processes were more standardised and the information flow were digital and had a process-oriented approach, so that urban environment applications and actors can share the information more easily.

This thesis aims to define prerequisites for achieving a more efficient digital flow of geographical information, with a special attention on serving the needs of urban environment applications in the planning and building process. The aim consists of six research objectives and the following conclusions can be drawn from the thesis:

Research objective 1: to study techniques for creating formal extensions of INSPIRE specifications and to evaluate the consequences of using extended INSPIRE dataset from both a user and a data provider perspective

This objective was examined in Paper I and examines harmonisation between geographic levels by developing a formal extension of the INSPIRE hydrography (INSPIRE HY) data specification. The study showed that it is possible to create a complex INSPIRE extension that incorporates all additional attributes, relations and object types that are included in the Swedish water system standard (SWSS; SS 637008:2015, 2015). From a data modelling perspective, it is faster to create and extension than to start the UML modelling from scratch. All INSPIRE application schemas are in English, this makes an extended INSPIRE schema more easily understood in other countries. This could also cause a problem for countries that require national schemas to be written in their own languages, and results in an extended INSPIRE schema written in mixed languages. Another disadvantage is that new objects and attributes must be added at the lowest level of the UML schema which makes the maintenance of such schema more cumbersome. Also, changes made to the INSPIRE schemas will affect the national schemas.

Results from the user-centric evaluation, where hydrological analyses were performed, show that to acquire data from a dataset that conforms to the extended INSPIRE HY do not differ in input of labour or time compared to acquiring it from an INSPIRE HY or SWSS dataset.

From a data provider perspective, it would be relatively simple to replace the two current download services with one for the extended INSPIRE HY. It is not possible to say if this saves any money as the assessment of development and maintenance costs are not structured in such way that this can be determined.

Research objective 2: to study how building parts are defined in specifications, to describe potential use of building parts, and consequences of the usage of them

This objective was evaluated in Paper II and examines harmonisation between hierarchic structures. The building part concept was studied in three geodata standards (CityGML, INSPIRE building and a Swedish specification for buildings) and in the BIM standard IFC. Building parts are defined in similar, but not identical ways in all the geodata standards, IFC does not include a building part feature, but a building in can consist of several other building features. The definitions are described as recommendations and not as requirements in all the specifications.

Building parts can for example be used by municipalities during the building permit process where an extension that has a different height than the original building can become a building part. Building parts could also facilitate the 3D property formation by creating building parts based on the current use of the building (e.g. residential). A BIM model can also affect the structure of building-building parts for a 3D geodata building. If a BIM models is used as the source for geodata buildings, the structure of building-building parts in the geodata building will probably be the same as in the BIM model. These different ways of dividing a building into building parts could have consequences when the building information is reused later on in a different context. A possible way to overcome this is to have clear guidelines on how to use building parts in a for example a national context.

Research objective 3: to create modelling guidelines for constructing 3D geodata building models to be used irrespective of the data source

This objective was evaluated as a part of Paper III and examines if the harmonisation between hierarchic structures could be improved by using guidelines. Modelling guidelines for constructing 3D geodata building models was created. Routines to create CityGML LOD1 and LOD2 building models from both BIM and ALS/footprint data using these modelling guidelines were then developed and tested.

Results show that it is possible to use the same modelling guidelines to extract CityGML data from both BIM and ALS/footprint data. The resulting CityGML models are visually and quantitatively similar and with a small relative difference between them. Some differences are due to different interpretations of the modelling guidelines. This shows the importance of thoroughly testing the guidelines before using them in a production environment.

Research objective 4: to develop and evaluate a proposal for a national building standard in Sweden

This objective was evaluated in Paper IV and examines among others the harmonisation between geographic levels and between hierarchic structures. Reasons for having a national standard for buildings are that a number of cities have created their own 3D city models and the requirements are becoming more complex, but still many 3D city models do not live up to their expectations. Paper IV describes the development of a proposed Swedish building standard as a CityGML 3.0 ADE that includes all national specific requirements. Test cases were set up and results show that the defined requirements were met. That is: to convert an IFC model to a dataset that conforms to the proposed standard (denoted CityGML Sve-Test), to use a CityGML Sve-Test to automatically check if a building conforms to the regulations in a detailed development plan, and to import and visualize CityGML Sve-Test datasets in two commercial software.

Developing a building standard at the national level that builds on an international standard (in this case CityGML) and incorporates all national requirements will ensure more harmonised structures, harmonised concepts and thereby a more harmonised exchange of building information within the country.

Research objective 5: to compare and evaluate three version management methods for 3D city models

This objective was evaluated in Paper V and examines harmonisation over time. More complex usage of 3D city models often require that the models are versioned. The Product Lifecycle Support (PLCS) standard is a comprehensive ISO standard, originally developed for the process industry, that could be used for this purpose. There are also two versioning methods especially designed for 3D city models available, the versioning in the proposed version 3.0 of CityGML, and a modified Git proposal implemented in CityJSON. The evaluation shows that PLSC meet all requirements, CityGML all but one. CityJSON is on purpose a simple solution that meets less requirements.

There are no versioning method for 3D city models that can be used for all purposes, the method should be chosen depending on the requirements. PLCS is a comprehensive lifecycle management standard that can be difficult to implement and use, but could be the solution if very complex version management is needed. The modified Git proposal on the other hand is a simple method that in many cases will suffice, while CityGML could be used when more versioning capabilities are required.

Research objective 6: to identify obstacles to version management of 3D city models, and to propose recommendations on how to overcome these obstacles

This objective was evaluated in Paper VI and examines among others harmonisation over time. Many applications require that 3D city models are linked to other registers, that the models include temporal information and are continuously updated. Versioning methods for 3D city models exist, but most models are still not versioned.

Reasons for why 3D city models are not versioned can be on many levels. Additional temporal information can be difficult for municipalities to collect and require restructuring of technical solutions and work processes. It can be difficult to implement the versioning method in a register database and to propagate these changes to the 3D city models. Finally applications must become better at handling standardised 3D city models and temporal information. To overcome this, data providers must have strong incentives to include versioning in 3D city models. Only capabilities required by applications should be implemented, to reduce the complexity of the solution. 3D city models should also link to the national building registers as it enables more complex use of the models, and ability for authorities to fetch required (versioning) information directly from the city model.

To summarise, this thesis has addressed several important issues for harmonisation of geographic data. It has shown that it is imperative to address data harmonisation from different aspects, in this case harmonisation between geographic levels, between hierarchic structures, and over time, to achieve a digital and process-oriented flow of geographic data. Even though the major part of the studies have concerned 3D building data, the outcome is applicable also to other geographic themes, especially 3D city models and on other man-made themes such as roads, tunnels and bridges. The main focus of the thesis has been on technical issues of the data harmonisation, but it must be noted that many of the studies have shown that also other types of issues can be of importance: having *guidelines* that guide users when creating e.g. 3D buildings in accordance with a comprehensive standard, such as CityGML (Paper II and III); collecting *requirements* from applications and users before the development of a national standard (Paper IV and V); and in order for more 3D city models to include lifecycle information and be versioned, data provider must have strong *incentives* to version their models and the *work flow* for collecting temporal information must be effective (Paper VI).

5.2 Outlook and open questions

This thesis has studied how harmonisation of geographic data can contribute to a more efficient digital information flow with a special attention on serving the needs of applications in the planning and building sector, and it has come up with a number of prerequisites for achieving this. The thesis also generates potentials for further studies and leave some open questions. Two of them are described here: 1) How can conversion between BIM and geodata models be better achieved? and 2) How can versioning and lifecycle management for 3D city models and 3D buildings be implemented to serve application needs?

The ability to convert data between BIM and geodata models is becoming increasingly important, as for example 3D buildings are described both as BIM and as geodata during its lifecycle. The GeoBIM benchmark project has shown that there are still many issues to overcome before a more correct conversion can be performed both from IFC to CityGML and from CityGML to IFC (Noardo et al., 2020a, 2020b and 2020c). Reasons for this are among others that the open standards are comprehensive, include complex representations, and describe recommendations instead of rules, which allows for various possible interpretations. The proposed ISO technical specification *Geographic information — BIM to GIS conceptual mapping (B2GM)* (ISO/TS 19166) include a conceptual framework for object mapping from a BIM model to a GIS model where data needed for a specific use case together with rulesets for the mapping can be described. A possible future study could compare the difference in two converted geodata models. In the first conversion, a standard BIM model is converted to a standard geodata model, and the second conversion the conversion follows the conceptual framework in ISO/TS 1966, in order to evaluate if this could enhance the conversion.

Versioning and lifecycle management for 3D city models and 3D buildings is an important prerequisite for a process-oriented digital information flow between different phases in the planning and building process. It must be possible to store and retrieve information about the whole lifecycle of for example a 3D building. A number of versioning methods exist (Eriksson et al., 2020b), but still a majority of openly available 3D city models are not versioned at all (Vitalis et al., 2019). In Eriksson et al. (2020c) we evaluate why so few 3D city models are versioned, even though there are requirements on the version management from several applications. Six issues were examined in this study and two of these could be further investigated in a future study: Are the versioning methods too difficult to implement? and Do the versioning methods fulfil the requirements for versioning for applications in the planning and building sector? The study by Eriksson et al. (2020c) include a conceptual description of difficulties that may arise when implementing a versioning method, but no practical tests were made. Nor was any database implementations of the new versioning module in CityGML 3.0 (Chaturvedi et al. 2016) or of the modified Git proposal (Vitalis et al., 2019) found in the literature. A future study could therefore perform a database implementation of the new versioning module in CityGML 3.0 by extending 3DCityDb with this information and also a database implementation of the modified Git proposal. Applications in the planning and building sector could then test to retrieve information from the databases. This would evaluate if the versioning methods fulfil the requirements of the applications, which information that must be stored in the database and which information that could be stored elsewhere.

6 References

Arroyo Ohori, K., Biljecki F., Diakité A., Krijnen T.F., Ledoux H., Stoter, J. (2017). Towards an integration of GIS and BIM data: What are the geometric and topological issues? *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., 4, 4W5:1-8.

Arroyo Ohori, K., Biljecki, F., Kumar, K., LeDoux, H., Stoter, J. (2018) Modeling Cities and Landscapes in 3D with CityGML. In *Building Information Modeling*, Springer Science and Business Media LLC, 199-215.

Atazadeh, B., Kalantari, M., Rajabifard, A., Ho, S., Ngo, T. (2017). Building information modelling for high-rise land administration. *Trans. GIS*, 21, 91-113.

Benner, J., Geiger, A., Häfele, K.H. (2010) Concept for Building Licensing Based on Standardized 3D Geo Information. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, XXXVIII-4/W15, 9-12.

Biljecki, F., Ledoux, H., Stoter, J. (2014). Redefining the level of detail for 3D models. *GIM Int*., 28, 21-23.

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., Çöltekin, A. (2015). Applications of 3D City Models: State of the Art Review. *Isprs Int. J. Geo-Inf*., 4, 2842-2889.

Biljecki, F., Kumar, K., Nagel, C. (2018). CityGML Application Domain Extension (ADE): overview of developments. *Open Geospat. Datasoftw. Stand.,* 3, 13.

Cetl, V., Tóth, K., Reznik, T., Tomas, R. (2012). Abstract Test Suite for INSPIRE Data Specifications, In: *Proceedings of INSPIRE Conference 2012*, Istanbul, Turkey.

Chaturvedi, K., Kolbe, T. H. (2019). A requirement analysis on extending semantic 3D city models for supporting time-dependent properties, *ISPRS Ann. Photogramm. Remote. Sens. Spat. Inf. Sci*., IV-4/W9, 19-26. https://doi.org/10.5194/isprs-annals-IV-4-W9-19-2019

Chaturvedi, K., Smyth, C. S., Gesquière, G., Kutzner, T., Kolbe, T. H. (2016). Managing versions and history within semantic 3D city models for the next generation of CityGML. In: *Advancing Geoinformation Science for a Changing World*, Springer Science and Business Media LLC, 191-206.

CityJSON. Specifications, 2019, https://cityjson.org/specs/

CoClass, 2016. Swedish digital construction classification system for built environment. https://byggtjanst.se/tjanster/coclass/

de Laat, R., van Berlo, L. (2010). Integration of BIM and GIS: The development of the CityGML GeoBIM extension, *Advances in 3D Geo-Information Sciences*, 211-225.

Deng, Y., Cheng, J.C.P., Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison, *Autom. Constr*., 67, 1-21.

DGIWG, (2010). Implementation Guide to the DGIWG Feature Data Dictionary (DFDD). https://www.dgiwg.org/dgiwg/htm/documents/standard_operating_procedures.htm

Directive 2007/2/EC of the European Parliament and of the Council establishing an Infrastructure for Spatial Information in the European Community (INSPIRE), (2007). http://inspire.ec.europa.eu/documents/directive-20072ec-european-parliament-and-council-14-march-2007-establishing.

El Arass, M., Souissi, N., (2018). Data lifecycle: from big data to SmartData, In *IEEE 5th International Congress on Information Science and Technology (CiSt)*, Marrakech, 80-87.

El Arass, M., Tikito, I., Souissi ,N., (2017). Data lifecycles analysis: towards intelligent cycle, In *Proceeding of the second International Conference on Intelligent Systems and Computer Vision*, ISC. doi:10.1109/ISACV.2017.8054938

El-Mekawy, M., Östman, A., Hijazi, I. (2012). A Unified Building Model for 3D Urban GIS, *ISPRS Int. J. Geo-Inf.,* 1, 120-145.

El-Mekawy, M. S. A., Paasch, J. M., Paulsson, J. (2015). Integration of legal aspects in 3D cadastral systems. *Int. J. E-Plan. Res*., 4, 47-71.

Eriksson, H., Harrie, L., Paasch, J. M., Persson, A. (2018a). Techniques for and consequences of using INSPIRE extensions: a case study with Swedish hydrological data. *Int. J. Spat. Data Infrastruct. Res*.,13, 172-201. (Paper I)

Eriksson, H., Harrie, L., Paasch J. M. (2018b). What is the need for building parts? - A comparison of CityGML, INSPIRE Building and a Swedish building standard. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*., XLII-4/W10, 27-32. doi: https://doi.org/10.5194/isprs-archives-XLII-4-W10-27-2018. (Paper II)

Eriksson, H., Johansson, T., Olsson, P.O., Andersson, M., Engvall, J., Hast, I., Harrie, L. (2020a). Requirements, Development, and Evaluation of a National Building Standard – *A Swedish Case Study. Isprs Int. J. Geo-Inf.,* 9, 78. doi: https://doi.org/10.3390/ijgi9020078. (Paper IV)

Eriksson, H., Sun, J., Tarandi, V., Harrie, L. (2020b). Comparison of versioning methods to improve the information flow in the planning and building processes, *Trans. GIS*, doi: https://doi.org/10.1111/tgis.12672. (Paper V)

Eriksson, H., Harrie, L. (2020c). Versioning of 3D city models – needs, obstacles and recommendations (Paper VI, Submitted)

Fernández-Freire, C., del-Bosque-González, I., Vicent-García, J. M., Pérez-Asensio, E., Fraguas-Bravo, A., Uriarte-González, A., Fábrega-Álvarez P., Parcero-Oubiña, C. (2013). A Cultural Heritage Application Schema: Achieving Interoperability of Cultural Heritage Data in INSPIRE, *Int. J. Spat. Data Infrastruct. Res.,* 8, 74-97.

Fichtinger, A., Rix, J., Schäffler, U., Michi, I., Gone, M., Reitz, T. (2011). Data Harmonisation Put into Practise by the HUMBOLDT Project, *Int. J. Spat. Data Infrastruct. Res*., 6, 234-260.

Góźdź, K., Pachelski, W., Van Oosterom, P., Coors, V. (2014). The possibilities of using CityGML for 3D representation of buildings in the cadastre. In: *Proceedings of the Fourth International FIG Workshop on 3D Cadastres Conference*, Dubai, United Arab Emirates, 339-352.

Gruber, U., Riecken, J., Seifert, M. (2014). Germany on the Way to 3D-Cadastre, In: *Proceedings of the FIG Congress*, Kuala Lumpur, Malaysia.

Gröger, G., Kolbe, T.H., Nagel, C., Häfele, K.H. (Eds.) OGC 12-019 OpenGIS City Geography Markup Language (CityGML) Encoding Standard, 2012. http://www.opengeospatial.org/standards/citygml.

Hallberg, D., Tarandi, V. (2011). On the Use of Open BIM and 4D Visualisation in a Predictive Life Cycle Management System for Construction Works, *J. Inf. Technol. Constr.*, 16.

INSPIRE Building, Data Specification on Buildings – Technical Guidelines, Version 3.0, (2013). http://inspire.ec.europa.eu/id/document/tg/bu.

INSPIRE Generic Conceptual Model, Version 3.4, (2014). https://inspire.ec.europa.eu/documents/inspire-generic-conceptual-model

INSPIRE Hydrography, Data Specification on Hydrography – Technical Guidelines, Version 3.1, (2014). http://inspire.ec.europa.eu/id/document/tg/hy.

INSPIRE Methodology for the development of data specifications, Version 3.0 (2008). https://inspire.ec.europa.eu/reports/ImplementingRules/DataSpecifications/D2.6_v3.0.pdf

Isikdag, U., Zlatanova, S., (2009) A SWOT analysis on the implementation of BIM within geospatial environment, in: A. Krek, M. Rumor, S. Zlatanova, E. Fendel (Eds.), *Urban and Regional data Management*, UDMS Annuals 2009, CRC Press, The Netherlands, 15-30.

ISO 10303-239:2012. Industrial automation systems and integration – Product data representation and exchange – Part 239: Application protocol: Product life cycle support (PLCS), 2012. https://www.iso.org/standard/54791.html

ISO 16739:2013. Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, 2013.

ISO 19115-1:2014. Geographic information – Metadata, 2014.

ISO 19128:2005. Geographic information – Web map server interface, 2005.

ISO 19131:2007. Geographic information – Data product specification, 2007.

ISO 19142:2010. Geographic information — Web Feature Service, 2010.

ISO 19152:2012. Geographic information – Land Administration Domain Model (LADM), 2012.

ISO 19157:2013. Geographic information — Data quality, 2013.

ISO 29481-1:2010(E). Building Information modelling - Information delivery manual - Part 1: Methodology and format, 2010. https://www.iso.org/standard/45501.html

ISO 6707-1:2014. Buildings and civil engineering works - Vocabulary - Part 1: General terms, 2014.

ISO 9001:2015. Quality management systems — Requirements, 2015.

ISO/TS 19166. Geographic information — BIM to GIS conceptual mapping (B2GM).

Julin, A., Jaalama, K., Virtanen, J.-P., Pouke, M., Ylipulli, J., Vaaja, M., Hyyppa, J., Hyyppä, H. (2018) Characterizing 3D City Modelling Projects: Towards a Harmonized Interoperable System. *Isprs Int. J. Geo-Inf.*, 7, 55.

Kang, T. (2018) Development of a Conceptual Mapping Standard to Link Building and Geospatial Information. *Isprs Int. J. Geo-Inf.*, 7, 162.

Kiviniemi, A., Codinhoto, R. (2014). Challenges in the implementation of BIM for FM: Case Manchester Town Hall complex. In *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Orlando, FL, 665-672.

Kumar, K., Ledoux, H., Commandeur, T.J.F., Stoter, J.E. (2017). Modelling urban noise in CityGML ADE: case of the Netherlands, In *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, Melbourne, Australia, IV-4/W5, 73-81.

Kumar, K., Labetski, A., Arroyo Ohori, K., Ledoux, H., Stoter, J. (2019). Harmonising the OGC Standards for the Built Environment: A CityGML Extension for LandInfra. *Isprs Int. J. Geo-Inf.*, 8, 246.

Kutzner, T., Kolbe, T. (2018). CityGML 3.0: Sneak Preview. In Proceedings of the PFGK18-Photogrammetrie-Fernerkundung-Geoinformatik-Kartographie, 37. Jahrestagung in München, Munich, 835-839.

Kutzner, T., Chaturvedi, K., Kolbe, T.H. (2020). CityGML 3.0: New Functions Open Up New Applications. *PFG* 88, 43-61. https://doi.org/10.1007/s41064-020-00095-z

Lee, J., Li, K.J., Zlatanova, S., Kolbe, T.H., Nagel, C., Becker, T., (2016). Eds. OGC IndoorGML, Version 1.0.2. OGC Document 14-005r4. Open Geospatial Consortium. https://www.opengeospatial.org/standards/indoorgml

Ledoux, H., Arroyo Ohori, K., Kumar, K., Dukai, B., Labetski, A., Vitalis, S. (2019). CityJSON: a compact and easy-to-use encoding of the CityGML data model. *Open Geospat. Datasoftw. Stand.*, 4, 4.

Lenk, A., Bonorden, L., Hellmanns, A., Roedder, N., Jaehnichen, S. (2015). Towards a taxonomy of standards in smart data, In *2015 IEEE International Conference on Big Data (Big Data)*, 1749-1754.

Levitin, A., Redman T. (1993). A Model of the Data (Life) Cycles with Application to Quality, *Inf. Softw. Technol.*, 35(4), 217-223.

Li, L., Wu, J., Zhu, H., Duan, X., Luo, F. (2016). 3D modeling of the ownership structure of condominium units. *Comput. Environ. Urban Syst.*, 59, 50-63.

Liu, X., Wang, X., Wright, G., Cheng, J.C.P., Li, X., Liu, R. (2017). A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS). *Isprs Int. J. Geo-Inf.*, 6, 53.

Löwner, M.-O., Gröger, G., Benner, J., Biljecki, F., Nagel, C. (2016). Proposal for a new LOD and Multi-Representation Concept for CityGML. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV(2/W1), 3-12

Meijer, M., Vullings, L.A.E., Bulens, J.D., Rip, F.I., Boss, M., Hazeu, G., Storm, M., (2015). Spatial Data Quality and a Workflow Tool, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*, XL-3/W3

Morshedzadeh, I. (2018). Multi-level management of discrete event simulation models in a product lifecycle management framework, *Proceedia Manuf.,* 25, 74-81.

Morton, P.J., Horne, M., Dalton, R.C., Thompson, E.M. (2012). Virtual city models: Avoidance of obsolescence, In *Digital Physicality – Proceedings of the 30th eCAADe Conference, Prague, Czech Republic*, (Eds.) Achten, H., Pavlicek, J., Hulin, J., Matejovska, D., Education and Research in Computer Aided Architectural Design in Europe-eCAADe: Brussels, Belgium, 213-224.

Nationell Informationsspecifikation Byggnad, version 1, 2019 https://www.lantmateriet.se/contentassets/ade15b08cbfe43fc95bf83e5f28c281d/natspec-byggnad-v1.0.pdf

Nebert, D. D. (2004). Developing Spatial Data Infrastructures: The SDI Cookbook. Version 2.0. *GSDI Association*. http://gsdiassociation.org/images/publications/cookbooks/SDI_Cookbook_GSDI_2004_ver2.pdf

Noardo, F., Ellul, C., Harrie, L., Overland, I., Shariat, M., Arroyo Ohori, K., Stoter, J. (2019). Opportunities and challenges for GeoBIM in Europe: developing a building permits use-case to raise awareness and examine technical interoperability challenges. *J. Spat. Sci*., 1-25.

Noardo, F., Harrie, L., Arroyo Ohori, K., Biljecki, F., Ellul, C., Eriksson, H., Guler, D., Hintz, D., Jadidi, M.A., Pla, M., Sanchez, S., Stouffs, R., Tekavec, J., Stoter, J. (2020a). Tools for BIM-GIS Integration (IFC Georeferencing and Conversions): Results from the GeoBIM Benchmark 2019. *Isprs Int. J. Geo-Inf*. 9, 502, doi:10.3390/ijgi9090502

Noardo, F., Krijnen T., Arroyo Ohori, K., Biljecki, F., Ellul, C., Harrie, L., Eriksson, H., Polia, L., Nebras Salheb, N., Tauscher, H., van Liempt, J., Goerne, H., Hintz, D., Kaiser, T., Leoni, C., Warcho, A., Stoter, J. (2020b). Reference study of IFC software support: the GeoBIM benchmark 2019 – Part I (Submitted 2020) https://arxiv.org/pdf/2007.10951.pdf

Noardo, F., Arroyo Ohori, K., Biljecki, F., Ellul, C., Harrie, L., Krijnen, T., Eriksson, H., van Liempt, J., Pla, M., Ruiz A., Hintz, D., Krueger, N., Leoni, C., Leoz, L., Moraru, D., Vitalis, S., Willkomm, P., Stoter, J. (2020c). Reference study of CityGML software support: the GeoBIM benchmark 2019 – Part II (Submitted 2020) https://arxiv.org/pdf/2007.10938.pdf

Nouvel, R., Bahu, J.M., Kaden, R., Kaempf, J., Cipriano, P., Lauster, M., Haefele, K.H., Munoz, E., Tournaire, O., Casper, E. (2015). Development of the CityGML Application Domain Extension Energy for Urban Energy Simulation, In *Proceedings of 14th Conference of International Building Performance Simulation Association*, Hyderabad, India, 559-564.

Nguyen, S. H., Kolbe, T. H. (2020). A multi-perspective approach to interpreting spatio-semantic changes of large 3D city models in CityGML using a graph database, *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*, VI-4/W1-2020.

Nguyen, S. H., Yao, Z., Kolbe, T. H. (2017). Spatio-semantic comparison of large 3D city models in CityGML Using a Graph Database. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., IV-4/W5, 99–106.

OGC API, API - Features - Part 1: Core, Open Geospatial Consortium, 2019. http://www.opengis.net/doc/IS/ogcapi-features-1/1.0

OGC CityGML3, CityGML 3.0 Conceptual Model, 2019. https://github.com/opengeospatial/CityGML-3.0CM

OGC LandInfra /InfraGML, OGC Land and Infrastructure Conceptual Model Standard, Open Geospatial Consortium, 2016. https://www.opengeospatial.org/standards/infragml

OGC quality-ie. OGC CityGML quality interoperability experiment, Open Geospatial Consortium, Document OGC 16-064, 2016. www.opengeospatial.net/doc/PER/citygml-quality-ie

Olsson, P.-O., Axelsson, J., Hooper, M., Harrie, L. (2018). Automation of Building Permission by Integration of BIM and Geospatial Data. *Isprs Int. J. Geo-Inf.*, 7, 307.

Olsson, P., Johansson, T., Eriksson, H., Lithén, T., Bengtsson, L.H., Axelsson, J., Roos, U., Neland, K., Rydén, B., Harrie, L. (2019). Unbroken digital data flow in the built environment process - a case study in Sweden. In *Proceedings of the ISPRS Geospatial Week*, Enschede, The Netherlands, XLII-2/W13.

Owen, R. (2009). CIB white paper on IDDS integrated design and delivery solutions. Delft, the Netherlands: CIB.

Pauknerova, E., Sidlichovsky, P., Urbanas, S., Med, M. (2016). The European Location Framework – From National to European, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, 41(B4), 181-186.

Paulsson, J., Paasch, J. M. (2013). 3D property research from a legal perspective. *Comput. Environ. Urban Syst.*, 40, 7-13.

Paviot, T., Cheutet, V., Lamouri, S. (2011). A PLCS framework for PDM/ERP interoperability. *Int. J. Prod. Lifecycle Manage.*, 5, 295-313.

Richen, A., Steinhorst, A., (2005). Standardization or Harmonization? You Need Both, In: BP Trends Newsletter, http://www.bptrends.com/publicationfiles/11-05-ART-StandardizationorHarmonizationvRickenSteinhorst.pdf

Roschlaub, R., Batscheider, J. (2018). Transformation of a Cadastre-Compliant 3D Building Model of Bavaria to INSPIRE. *Int. J. Spat. Data Infrastruct. Res.*, 13, 62-77.

SIG3D QualityWorking Group, (2017). Modeling Guide for 3D Objects Part2: Modeling of Buildings (LoD1, LoD2 and LoD3), Version 2.0.1 EN. https://files.sig3d.org/file/ag-qualitaet/201711_SIG3D_Modeling_Guide_for_3D_Objects_Part_2.pdf

SS 637008:2015 (2015). Geographic information – Water Systems – Rules for national applications and for the INSPIRE hydrography theme.

Stark, J. (2015). Product lifecycle management: Paradigm for 21st century product realization (Vol. 1, 3rd ed.). Cham, Switzerland, Springer.

Sun J., Olsson P.-O., Eriksson H., Harrie L. (2019a). Evaluating the geometric aspects of integrating BIM data into city models, *J. Spat. Sci*, doi: https://doi.org/10.1080/14498596.2019.1636722

Sun, J., Mi, S., Olsson, P.-O., Paulsson, J., Harrie, L. (2019b). Utilizing BIM and GIS for Representation and Visualization of 3D Cadastre. *ISPRS Int. J. Geo-Inf.,* 8, 503-527, doi: 10.3390/ijgi8110503.

Svensk Geoprocess building (2018). Geodataspecifikation Byggnad, Version 3.0, https://www.lantmateriet.se/contentassets/e4b0b7cb457045c7bd3ce794e625b154/sgp_geodataspecifikation_byggnad_v3.0test1.pdf

Svensk Geoprocess guidelines (2018). Mätningsanvisningar Geometrisk representation vid utbyte. https://www.lantmateriet.se/contentassets/ebf6dbb6f41743f8b21754bc46a2386d/sgp_matningsanvisningar_v3.2.pdf

Svensk Geoprocess water (2017). Geodataspecifikation Vatten, Version 3.0 Test 1, https://www.lantmateriet.se/contentassets/e4b0b7cb457045c7bd3ce794e625b154/sgp_geodataspecifikation_vatten_v3.0test1.pdf

Tamash, N., (2012). INSPIRE Compliant Datasets Transformation & Conformance Testing, *MSc Thesis, Geographical Information Management & Applications (GIMA)*, Utrecht University.

Tarandi, V. (2015). A BIM Collaboration Lab for Improved through Life Support. *Procedia Econ. Financ*., 21, 383-390.

Tegtmeier, W., Zlatanova, S., Van Oosterom, P., Hack, H. (2014). 3D-GEM: Geo-technical extension towards an integrated 3D information model for infrastructural development. *Comput. Geosci.*, 64, 126-135.

Terzi, S., Bouras, A., Garetti, M., Kiritsis, D. (2010). Product lifecycle management: From its history to its new role. *Int. J. Prod. Lifecycle Manage.,* 4, 360-389.

UNCEFACT, (2012) http://tfig.unece.org/contents/data-harmonization.htm

van Berlo, L., Dijkmans, T., Stoter, J. (2013). Experiment for integrating Dutch 3D spatial planning and BIM for checking building permits. *Isprs Ann. Photogramm. Remote. Sens. Spat. Inf. Sci*., 2, 279-284.

Vadoudi, K., Allais, R., Reyes, T., Troussier, N. (2014). Sustainable product lifecycle management and territoriality: New structure for PLM. In S. Fukuda, A. Bernard, B. Gurumoorthy, & A. Bouras (Eds.), Product lifecycle management for a global market: PLM 2014, Berlin, Germany, Springer, 442, 475-484.

Vitalis, S., Labetski, A., Arroyo Ohori, K., Ledoux, H., Stoter, J. (2019). A data structure to incorporate versioning in 3D city models. *ISPRS Ann. Photogramm. Remote. Sens. Spat. Inf. Sci.*, 4, 123-130.

Wieland M., Pittore M. (2017). A spatio-temporal building exposure database and information life-cycle management solution, *Isprs Int. J. Geo-Inf.* 6, 114.

Worboys M. F., Duckham M. (2004). GIS: A Computing Perspective. *CRC Press*, Boca Raton, FL, 2nd edition, Chapter 10.

Worboys M. F. (2005). Event-oriented approaches to geographic phenomena, *Int. J. Geogr. Inf. Sci.*, 19(1), 1-28.

Yao, Z., Nagel, C., Kunde, F., Hudra, G., Willkomm, P., Donaubauer, A., Adolphi T., Kolbe, T.H. (2018). 3DCityDB - a 3D geodatabase solution for the management, analysis, and visualization of semantic 3D city models based on CityGML. *Open Geospatial Data, Softw. Stand.* 3, 5. https://doi.org/10.1186/s40965-018-0046-7

Yu J., (2015). A model for tracing cross-referenced statement validity, *Comput. Stand. Inter.*41, 10-16

Avhandlingar från Institutionen för naturgeografi och ekosystemanalys (INES), Lunds universitet
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