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Geomatics for the Built Environment

INTEGRATION OF 3D CITY MODELS IN A COUNTRY WIDE COVERING 3D BASEMAP

a case study in The Netherlands

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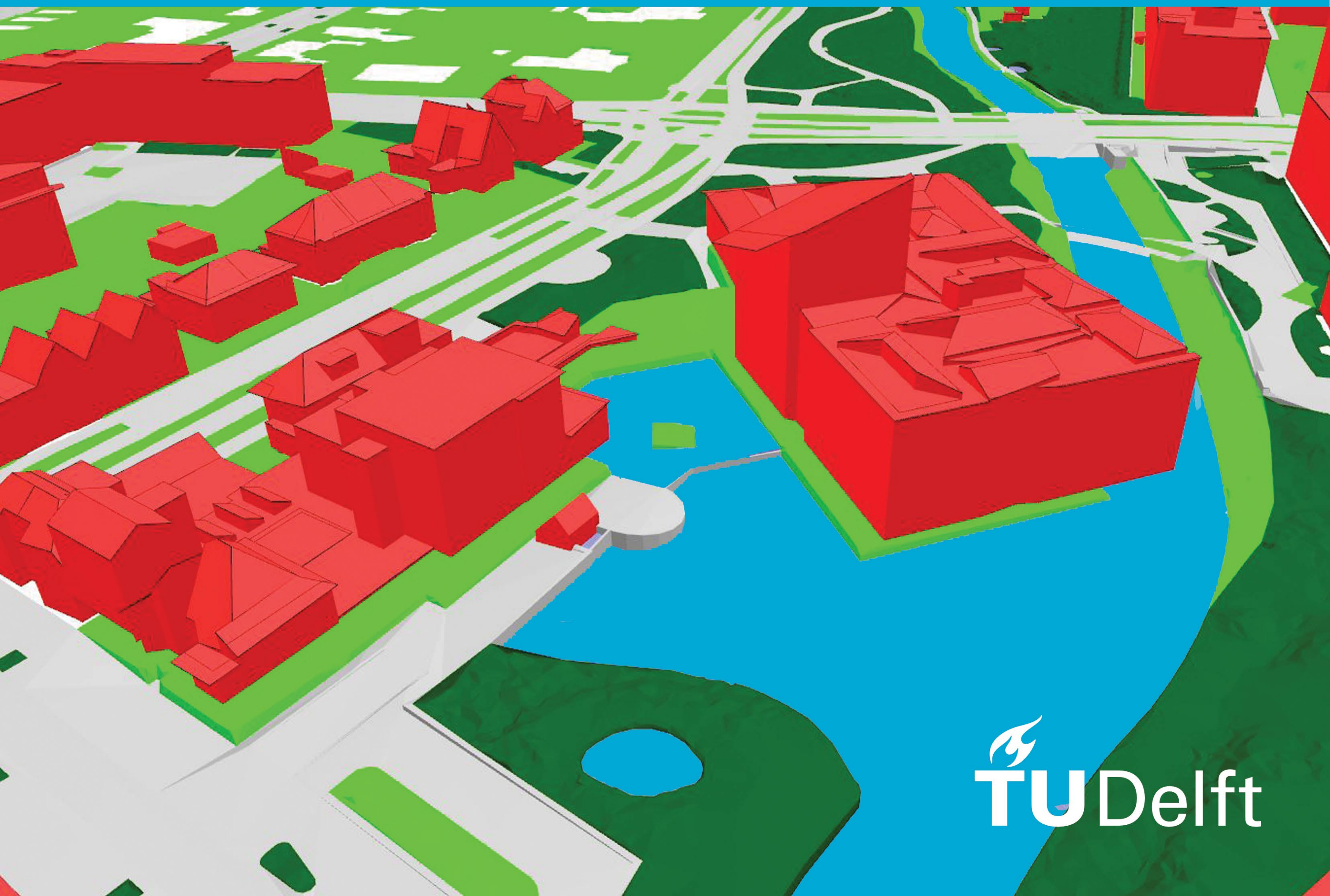

INTEGRATION OF 3D CITY MODELS IN A COUNTRY WIDE COVERING 3D BASEMAP

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ABSTRACT

The needs and interests for 3D data based on large-scale topography are increasing. A wide variety of these 3D data needs have emerged in multiple domains and for many different applications. Though, research have shown that the interoperability of this 3D data nowadays still is a challenging task. Many barriers are caused by different perspectives of organisations, technical issues during conversions of data and a lack of guidelines.

For this research, a case study is done in The Netherlands, one of the countries that experimented a lot with topographical data already. The Dutch Cadastre, Kadaster, has been working on a country wide covering 3D topographical basemap. However, also some of the Dutch source holders of large-scale topography have taken steps towards the development of 3D city models. The question that now arises, and also the main research question of this thesis, is: *"How can a variety of 3D city models be integrated in a country wide covering 3D basemap based on large-scale topography?"*.

In order to achieve an answer to this question, the methodology has been split up into three components. The first component contained a literature study on 3D city models. The second component of the methodology included the interaction with stakeholders, such as Kadaster and various source holders of the Dutch topographical data. This interaction is performed by means of interviews and surveys. The third component contained the technical part, in which different 3D test data is collected and compared.

The test data is for almost all stakeholders provided in CityGML, which is an international 3D standard used for 3D models. Various differences in the 3D data of the stakeholders are found. These differences can be found in the contents, the source data, the process and the management. Based on these test data and their differences, a workflow is developed in order to integrate the data. This workflow uses open source tools as *cjio* and *citygml4j* for the manipulation, integration and conversion of the data. This resulted in an integrated 3D model, containing both the data from Kadaster as well as the data from the source holders. Results have shown that the differences between the test data, semantically as well as geometrically, led to gaps and height differences in the final integrated model.

This study has proven that different 3D city models can be integrated in a country wide covering model, which can be converted to various formats (CityGML, CityJSON and OBJ). A workflow is developed that integrates the test data of 5 Dutch source holders with the data from Kadaster. A few challenges during the conversion and integration of data had to be overcome. These challenges were either caused by errors in the code of the test data or by bugs and errors in the software tools. In the end, two proposals were given for further organisational developments towards a national 3D basemap based on large-scale topographical data. These proposals were based on the results of the literature study, the interviews with stakeholders and the data comparison and integration. In option 1, a national 3D basemap, developed and managed by Kadaster, is proposed. In option 2, a new basis registration, the *3D BGT*, is proposed. In this situation Kadaster will provide a 3D basemap once and the source holders will collect and parse the mutations in 3D.

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1 INTRODUCTION

1.1 MOTIVATION

Nowadays large-scale topography maps are indispensable in the daily use for both the private and the public sector. These topographical maps contain geo-information about all features that appear on the Earth's surface. The features are displayed at a highly detailed level and include for example roads, buildings, borders, waterworks and land cover. Though this 2D geo-information is still widely used, also the needs and interests for topographical 3D data are increasing [Shiode, 2012].

A wide variety of 3D data needs have emerged in multiple domains and for many different applications. Investigations on the purposes of 3D data have been done and include applications for spatial planning, noise propagation and shadow estimation [Ho et al., 2018]. The requirements the 3D data must meet depend a lot on the application it will be used for. Mapping agencies and organisations in countries all over the world are aiming more and more towards the managing of 3D topographic data. These organisations are all in a different development phase and have different approaches towards the managing and formatting of the 3D data. This has led to the emergence of a wide variety of 3D models [Stoter et al., 2017b].

The Netherlands is one of the countries that experimented a lot with topographical 3D data already. The basic registration of large-scale topography (Basisregistratie Grootschalige Topografie (BGT)) is one of the ten basic registrations in the Netherlands, which are mandatory by law since 2016. The digital map of the large-scale topography is being collected and maintained by source holders. These source holders are each responsible for their own region and include all municipalities, provinces, water boards, ProRail and multiple ministries. The data is then managed by the Dutch Kadaster, who facilitates the national supply of the BGT products. Since the start of the 3D Pilot, an initiative that was set up to examine the use of 3D geo-information, Kadaster has been working on a country-wide covering 3D topographical basemap. The resulting 3D model is based on the large-scale topographic data and the basic registrations for buildings and addresses (Basisregistratie Adressen en Gebouwen (BAG)). Height values are retrieved from both the national elevation map (algemene hoogtekaart Nederland (AHN)) as well as dense image matching from aerial imagery [Goos et al., 2011].

1.1.1 Problem definition

As stated before, Kadaster has taken steps towards a 3D national basemap. However, also some of the Dutch source holders have taken steps towards a 3D approach of their data management. They have been, or are currently, developing 3D city models of their own regions. These 3D city models are different from the 3D basemap of the Cadastre, but also from each other in several ways. Differences can be expected in their contents, level of detail, data quality, completeness and actuality among other things. Despite knowing there that are national developments towards 3D data based on large-scale topography, the current state of developments, the data itself and the perspective from the source holders are not yet examined and thus remain unclear.

As described by Julin et al. [2018], the interoperability of 3D city models is still a challenging task. Many barriers increase the complexity of this process. Differences can be found in the modelling, in perspectives from different organisations, in missing guidelines, in ambiguities in terminology and in challenges during the conversion of data. A better interoperability and exchange of data has many benefits. This would for example prevent the generation and collection of the same data by multiple users, which thus would save a lot of costs and time. The question now arises if an integrated approach towards topographical 3D data is possible and desirable. For this research a case study will be done in the Netherlands, in collaboration with six stakeholders that are involved in the generation of large-scale topographical 3D models.

1.2 RESEARCH OBJECTIVES

The main research question for this thesis is stated as following:

- How can a variety of 3D city models be integrated in a country wide covering 3D basemap based on large-scale topography?

In order to answer the above question, this research is done in collaboration with Kadaster and a variety of large-scale topography source holders in the Netherlands. Multiple resources are deployed to study the current state of art of 3D data and the needs and requirements of the stakeholders. These resources include surveys, meetings and an exchange of 3D data. The following sub questions are also examined in this study.

- What is the state of art of large-scale topography 2D data in the Netherlands? Who are involved in the collection, development and managing of this data?
- What can be considered a 3D city model? What tools and software are used to generate and manage these 3D models?
- Which standards and formats apply to 3D data?
- What are the differences between existing 3D models in the Netherlands?
- Who are the potential users of 3D data? For which purposes do they use these 3D data and what are therefor their data needs?
- Who are the stakeholders and what are their needs and requirements concerning the integration of their 3D data? What would be their role concerning an integral approach of a national 3D model?

1.3 METHODOLOGY

In order to achieve the research goals and formulate an answer to the main question, the methodology has been split up into three components. At the beginning a literature study will be done on 3D models of large-scale topography. The current state of art and the developments of 3D data will be described. Questions about the use, requirements and different interests of 3D city models will also be examined. The second component of the methodology contains the interaction with stakeholders, which will be described in Section 1.3.1. The third component includes the technical part of the research: the comparing and integration of data. This component will be further explained in 1.3.2.

1.3.1 Surveys and meetings stakeholders

The second component of the methodology of this research contains the interaction with stakeholders. Not only the technical aspects, but also the role and wishes of the stakeholders have to be taken into account during the research. The stakeholders include all instances that manage, create or distribute large-scale topography. Some of these instance in the Netherlands have been (or are currently) using this data to generate 3D models. For this research six of these instances are contacted whom agreed to collaborate and provide their 3D data. These six stakeholders and the names of the contact(s) are listed Chapter 3. Surveys have been send out to them in order to give answers to various questions, divided in different categories.

After the surveys had been sent out, interviews with the stakeholders have been planned. The interviews have all taken place in the first phase of the thesis. The purpose of those interviews is to gain deeper insights of the use of the 3D data and the requirements and needs of the stakeholders. Follow-up meetings were planned in the last phase of the thesis, in order to gain feedback on the results.

1.3.2 Data comparison and integration

The third component of the methodology contains the comparing, merging and integration of the different 3D test data. The test data is located in five places: Eindhoven, Den Haag, Rotterdam, Amsterdam and Baarle-Nassau (Noord-Brabant). For each of these locations an associating CityGML model is generated by Kadaster. Based on this data, a workflow is developed in order to integrate the different 3D city models.

1.4 RESEARCH SCOPE

The research focuses on 3D models of large-scale topography in the Netherlands. The data that is used is provided by the stakeholders during the first phase of the thesis, so the outcome is based on the current state of their 3D data. Though, the developments concerning the collection, generation and management of 3D models kept evolving throughout the research.

For the outcome of the thesis, the use and purposes of 3D data is taken into account. This is done based on the result of existing literature. Thus a study to the purposes of 3D models and their requirements does not lie within the scope of this research.

1.5 READING GUIDE

In Chapter 2, the literature and works related to this research topic are described. This Chapter examines the specifications of 3D standards and define multiple use cases and applications of 3D city models. Chapter 3 describes the method as proposed for this research. Three different components of the method are defined and further described. In Chapter 4 the implementation and experiments of the method are described, also tools and datasets are described. The results of this implementation is described and visualised in Chapter 5. Chapter 6 is the conclusion where an answer to the main research question is provided. Also a discussion and future work section are included in this Chapter.

2 RELATED WORK

This Chapter will elaborate on the related work of this research, in order to get familiar with the topic and form answers to some of the research questions. In this Chapter an overview of the theories and work related to this research will be provided. At first, in Section 2.1, the concept of large-scale topography and its developments will be discussed. This Section will also elaborate on the basis registrations in The Netherlands, of which the BGT is a part. The second part, Section 2.2, will describe the construction and formatting of 3D city models. Since this research uses CityGML and CityJSON, both data models will be further discussed. After this, Section 2.3 will describe and discuss different use cases of 3D city models. Lastly, Section 2.4 will elaborate on the value measurement, as investigated by different researchers.

2.1 LARGE-SCALE TOPOGRAPHY

2.1.1 Large-scale topographic maps

In this first Section, the concept of large-scale topographic data will be reviewed. The most distinctive characteristic of a topographic map, is that it contains geo-information about all features that appear on the Earth's surface. The Earth's three-dimensional landscape is thus portrayed in a two-dimensional representation, modelled with the use of contour lines. The features include both man-made as well as natural features and are displayed accurately and in a highly detailed level. [Canada, 2014] Examples of these features are: roads, railways, rivers, lakes, buildings, bridges and vegetation. Also features are included that aren't visible in the real world, as for example: geographical names, elevation and border lines. Another important aspect of a topographic map is scale. A map is a modelled representation of the real world and therefore the features are reduced in size. The research of this thesis is focused on large-scale topography. Typically large-scale topographic maps show a smaller amount of area, with a greater amount of detail. [Dempsey, 2011] The uses of large-scale topographic maps can be found in a wide variety of domains and applications. Nowadays it can be stated that they are in indispensable tool for governments, science, urban planning, civil engineering and recreational uses among others. [Pavlicko and Peterson, 2017] Topographic maps and geographic information of a country are often produced by national mapping agencies. These agencies are usually publicly owned and may also deal with cadastral matters, as for example the Dutch Kadaster.

2.1.2 Basic Registrations in the Netherlands

The Netherlands had been introduced to the System of Basic Registrations, as initialised by the Ministry of the Interior and Kingdom Relations. This system is a whole of agreements and supplies, focused on the collection and management of data about about topography, citizens, companies, addresses and more. During the use of this data, the privacy of citizens is guaranteed. The system (see Figure 2.1) holds agreements about:

- The data collection
- The rules, dependencies and mutual relationships.
- The common facilities for the exchange and access of data.

The System of Basic Registrations is based on the following principles:

- Data will be collected and delivered only once and will have multiple uses.
- Obligated use of the data by governmental agencies.
- The government user has the duty to report errors.
- The basis registration source holders have the duty to examine the reported error.
- Every basic registration has a quality system in order to achieve the highest quality possible.
- Improve the interoperability and the exchange of data and processes.

The system contains 10 different basic registrations. Different roles have been determined for each of these registrations. The five roles that have been distinguished, are: the client, the supervisor, the source holder, the provider and the user. An organisation could have multiple roles. Two of the basic registrations, which are related to this research, are the BGT and the BAG. [PSB, 2010]

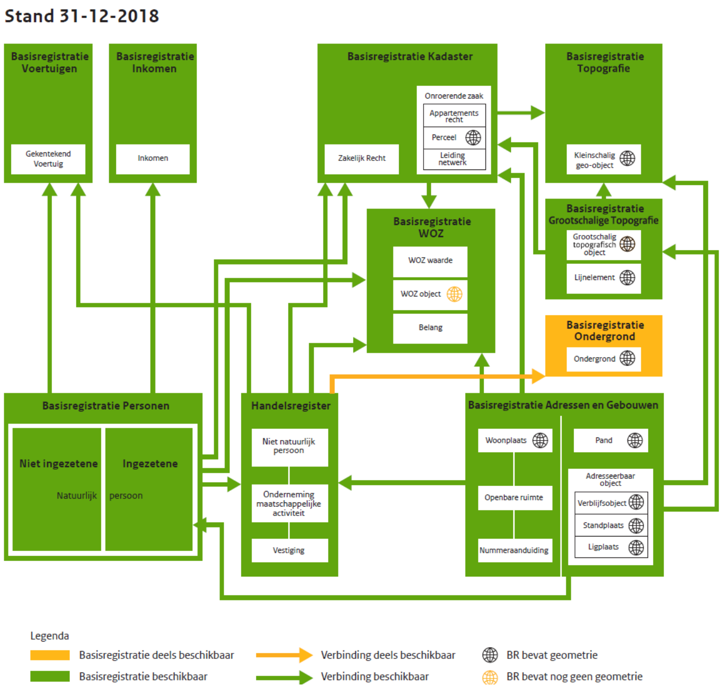


Figure 2.1: State of art of the System of Basic Registrations on 31/12/2018 [Bakkeren, 2015]

BGT

The BGT is the register that manages the national large-scale topographical data. The data covers the full country and is intended for use on a scale from 1:500 up to 1:5000. The data has to meet certain requirements concerning actuality, accuracy and completeness. The topographical objects that can be found in the BGT are amongst others: buildings, roads, railways, water and vegetation. [van den Brink et al., 2013a]

The division of roles concerning the BGT is as followed: The Ministry of Interior and Kingdom Relations is the client and also fulfils the role as supervisor, together with the source holders. The source holder is a group that exists of multiple governmental agencies, each responsible for the collection of data in their own region. The source holders include: all municipalities, all provinces, the Water Boards, the Ministry of Defense, the Ministry of Economic Affairs, ProRail and Rijkswaterstaat. Kadaster fulfils the role as provider, as they manage and facilitate the data.

The contents of the BGT is tailored to the information needs of the different end-users. The information model that is used to store the data, is Informatiemodel Geografie (IMGeo). This information model describes how object-oriented geo-information will be determined and stored, in a way that national exchange of the data is possible. The first version 1.0 was determined in 2010. The collaboration with the BGT lead to a new version 2.0 in 2012. The BGT is fully included in IMGeo, which is the mandatory part. The second part of IMGeo is optional and makes it possible to store an extra amount of information (attributes). The BGT objects have their own unique ID, but also aim to be directly linked to other geo-information. This resulted in the added attribute 'identificatieBAG', which links to the BAG. [van den Brink et al., 2013a]

Topographic objects can occur on multiple levels, for example when a road crosses water. The BGT makes it possible to register multiple objects that are on different levels relative to the Earth's surface. However, all objects that do have their geometry at ground level, form together a country-covering surface of the Netherlands. Thus objects at ground level may not overlap or have gaps between them. [van den Brink et al., 2013a]

BAG

The BAG is the basic registration that aims to identify and indicate unique addresses and buildings. Addresses and the objects the address applies to, are clearly linked to one another. For this basic registration the Ministry of the Interior and Kingdom Relations is also the client. The municipalities fulfil the role as both source holder as well as supervisor. Every municipality is source holder of the BAG within its own area. It is possible that multiple objects in the BAG that are related to each other, could lie within different municipalities. In the exceptional case when one building lies in two areas, the object will be registered in the municipality on whose territory the majority of the property is located. The geometry of the objects refers to the perpendicular top view of the object with its true shape, size, orientation and position with respect to the Earth. This view includes all visible and invisible parts above and below the ground, excluding the parts that can move. [Kooij et al., 2018]

2.1.3 Movement towards 3D

Nowadays large-scale topography maps and data are indispensable in the daily use for both the private and the public sector. Though this 2D geo-information is still widely used, also the needs and interests for topographical 3D data are increasing [Oude Elberink and Vosselman, 2006] [Shiode, 2012]. Mapping agencies and organisations in countries all over the world are aiming more and more towards the managing of 3D topographic data. These organisations are all in a different development phase and have different approaches towards the managing and formatting of the 3D data. This has led to the emergence of a wide variety of 3D models [Stoter et al., 2017b]. Specifically, the interest in the construction of 3D models of urban and built environment is growing. A host of digital mapping and rendering techniques are being developed for these 3D models. Shiode [2012] states that a wide variety of users try to develop and utilise 3D models or the urban environment, in order to plan and monitor services and impacts. The users include amongst other: central and local governments, urban and rural planners, environmental agencies, telecommunications and utility companies, consultants, architects and engineers.

Over the last 20 years, many researches and initiatives have been set up in order to examine the state of art of 3D urban models, their functionality and standards. One of these initiatives is called the Action, which took place between 2008-2012. Billen et al. [2014] elaborates on the aim of this Action, which was to explore different ways to semantically enrich 3D models and defines a city model as: "a representation of a part of the real world that encompasses urban entities and the global urban environment where they are located".

The Dutch initiative is called the 3D pilot, a two-phases project which started in 2010. The pilot was initiated by Kadaster, Geonovum (the national Spatial Data Infrastructure (SDI) executive committee in the Netherlands), the Netherlands Geodetic Commission (NGC), and the Dutch Ministry of Infrastructure and Environment. The first phase aimed at an establishment of a uniform approach for acquiring, maintaining, and disseminating 3D geo-information. Berntssen et al. [2012], Berlo et al. [2011] and Goos et al. [2011] describe the findings of respectively the 3D use cases, 3D standards and supply of 3D geo-information. The pilot resulted in a national 3D standard CityGML Application Domain Extension (ADE) that integrates with a new version of the national Information Model for Geo-Information (IMGeo) [Nl et al., 2011]. The second phase of the pilot distinguishes six activities. The activity of designing the standard specification for the construction of 3D IMGeo data is defined by Blaauboer et al. [2017].

2.2 3D CITY MODELS

As stated in the previous Section, the use of 3D models of the urban environment (also referred to as 3D city models), is growing rapidly. As mentioned by Biljecki et al. [2016], these 3D models where mainly used for visualisation purposes in the field of computer graphics. Nowadays the use of 3D city models can be found in a wide variety of domains. In a 3D city model, features that exist on the Earth's surface are represented by 3D objects. These objects include for example: buildings, bridges, vegetation, roads etc. All features that are existing in large-scale topographic maps, could be modelled in a three-dimensional way. This Section will firstly elaborate on the different techniques used to construct 3D city models. Secondly, an overview of different types of source data will be given. After this, different standards for 3D city models will be explained, focusing on CityGML and CityJSON. The last part will describe the 3D information model that is developed to define specifications on how to store and manage 3D geo-information.

2.2.1 Construction 3D city models

Many different techniques, tools and data sources are used in the construction of 3D city models. The methods to create 3D city models vary and depend on the available data resources. Researchers are still trying to develop more efficient and effective methods. [Kobayashi, 2006] The two technologies that are the most commonly used in the extracting of 3D geometries, are photogrammetry-based technologies and laser scanning based technologies. Out of those two technologies, aerial photos derived from airborne photogrammetry is the most often used during the construction of the 3D city models. [Singh, 2013] Photos can be derived in multiple ways: from aerial surveys, Unmanned Airborne Vehicle (UAV)'s, ground based mobile and static imagery (ranging from GoPro through purpose-built air survey camera systems). These technologies are able to construct different 3D data, as for example 3D mesh models, point cloud data, Digital Elevation Model (DSM)'s and true ortho images. [Coumans, 2017] A true ortho image is defined by Habib et al. [2006] as: "An ortho-photo in which surface elements that are not included in the Digital Terrein Model (DTM) are rectified to the orthogonal projection. These elements are usually buildings and bridges.". The construction methods can be mainly categorized into three approaches: [Kobayashi, 2006]

1. **Automatic:** Automatically approach towards the generation of 3D object extraction from images, using image processing and pattern recognition technologies.

2. **Semi-automatic:** An approach to generate 3D objects one by one with the support of technologies like photogrammetry and 3D vision.

3. **Manual:** Creating the objects geometries one by one, using CAD and CG software packages.

The chosen technique to construct 3D city models, thus heavily depends on the available resources. Costs, time and knowledge of the processes play a big role determining the most efficient and effective construction method for a certain purpose. The purpose could vary from the desire to a geometrically accurate model, to a more visually appealing model. For example, textures, derived from optical imagery, are used to improve the visual quality of 3D city models. As mentioned by Buyukdemircioglu et al. [2018], untextured 3D city models will always be visually incomplete, regardless of the level of detail in their geometries.

Photogrammetry
The photogrammetry-based approach is the most preferred technology in data production for 3D city models. The technique offers a good alternative for the manual measuring of objects as buildings, which usually demands a lot of time, money and labor. [Buyukdemircioglu et al., 2018] The main purpose of photogrammetry is to derive the shape and location of objects, in order to reconstruct objects and surfaces in 3D. This reconstruction of an object could be done in either a digital form (coordinates and derived geometric elements) or a graphical form (images, drawings, maps). Photogrammetry techniques can be applied on all objects that can be photographically recorded.

Photogrammetry is a technique where measurements are derived from multiple overlapping photographs, in order to create 3D objects. Knowing the position of the camera, the X, Y and Z coordinates for each pixel in the image can be estimated. [Mason] When multiple images are made of an object and a straight line is drawn from the camera centre through a pixel in the image, the multiple lines will intersect. This intersection is the 3D location of the object point (see Figure 2.2). [Kodde, 2016] Highly accurate and realistic textured 3D models are the result of photogrammetry. The very impressive results ensure an increasing usability of the photogrammetry techniques, which are still being improved and developed. [Mason] A lot of research has been done on the differences between photogrammetry and laser-based techniques. The research from Singh [2013] states that the accuracy of photogrammetry is better than the laser methods and furthermore the density of surface points is much higher in images.

Photogrammetry can be categorised in multiple ways. The first one categorises based on the position of the camera and distance to the objects that are being photographed. Five categories are distinguished: satellite, aerial, terrestrial, close range and macro photogrammetry. Another categorisation can be done on the amount of measurement images used in the technique. The categories vary from single image photogrammetry, to stereo-photogrammetry and multi-image photogrammetry. [Granshaw, 2010]

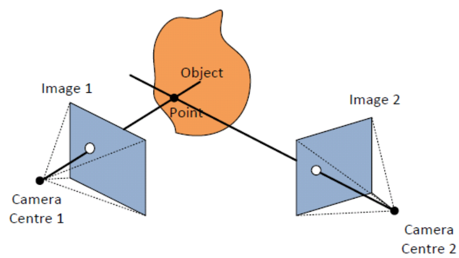


Figure 2.2: Principle 3D point construction with photogrammetry [Kodde, 2016]

DIM
Dense Image Matching (DIM) is one of the techniques within photogrammetry, that is used for the reconstruction of 3D models. The technique aims at computing a depth value for each pixel of an image, which lead to the generation of accurate and highly detailed DSM's. [Deuber et al., 2014] The technique enables the automatic extraction of 3D city models, whereas for standard traditional photogrammetry the result is a 2D product or perhaps a DSM and most vector data products are an abstract of the source content. The application of DIM techniques result in the creation of more realistic and highly accurate 3D models. These models could be presented as for example mesh models or point clouds. One of the big advantages of DIM as mentioned by Coumans [2017], is the minimal need of resource requirements.

Laser

The second approach that is used to construct 3D city models, is laser-scanning based. The technique that is used is called Light Detection and Ranging (LiDAR) and uses pulses of light that are send to the Earth's surface. The duration of the reflected signals of these light pulses are measured, in order to measure the distance between the laser scanner and the targeted object on the Earth's surface. Also knowing the accurate position of the laser instrument, the coordinates of the targeted object can be calculated in 3D (X, Y and Z). Just as with photogrammetry, the technique can be executed from different levels, for LiDAR two approaches are distinguished. The first approach is based on airborne laser-scanning and the second one on terrestrial laser-scanning, where the data is retrieved at ground level. Vehicles as airplanes and helicopters, are used to acquire the LiDAR data from an airborne perspective. This data is often used for the generation of DSM's and DTM's. The data acquired by terrestrial laser-scanning is mainly used for more detailed and complicated geometries of buildings and other objects. [Kobayashi, 2006] Many studies have been done on the automatic reconstruction of 3D city models and automatic building recognition. Over the past decades, the techniques and tools have improved a lot. Whereas the point density of LiDAR 10 years ago was about 1 point per 4x4 meter, nowadays the density could go up to over 1000 points per meter. This density is highly depending on the applied method. [Kodors and Kangro, 2017]

AHN

One of the datasets, as a result of laseralitmetry, is the Dutch AHN. This digital height map contains very accurate and detailed height information for the full country of the Netherlands. The height values in this dataset are related to the Normaal Amsterdams Peil (NAP). The results of the height measurements, are included in different products. These products are divided in raster data (DTM and DSM) and point cloud data (LAS file). The point cloud data is about 10% compressed and distributed as an LAZ (LAS zip) file. [https://www.ahn.nl/]

In the Netherlands, the AHN is a very import data source for the Water Boards, Provinces and the Directorate-General for Public Works and Water Management (Dutch: *Rijkswaterstaat*). The initiative for a digital height map resulted from the collaboration between these organisations, who also funded the program. Also other organisations as municipalities, research institutes and mapping agencies make use of the digital height map.

The first version of the height map (AHN1) was measured between 1997 and 2003. The point density of this data varies from 1 point per 16 m2 up to 1 point per m2. After a couple of years, the need of a more accurate and detailed map arose. This resulted in the second version (AHN2), which is collected between 2007 and 2012. Whereas the accuracy of the points in AHN1 was about 50cm, the accuracy for the AHN2 is 20cm. The point density varies between 6 and 10 points per m2. For the newest version, AHN3, the data collection started in 2014 until currently. [Leusink, 2019] In this version the classification of different features is added as attribute. Plans for the fourth version (AHN4) in the nearby future are already announced, as stated by Leusink [2019], The maps are all open data and are available trough Publieke Dienstverlening Op de Kaart (PDOK) and the National Georegister.

3dfier

An example of software that constructs 3D city models is 3dfier. The software is developed by the 3D Geoinformation group of Delft University of Technology, in collaboration with Kadaster, Amsterdam Institute for Advanced Metropolitan Solutions (AMS) and Stichting Technische Wetenschappen (STW). This open source software is able to create generate 3D models out of different data sources. Every polygon in the original 2D data set will be lifted to 3D, depending on their classification. Water polygons are converted to horizontal surfaces, buildings are extruded as LOD1 building blocks, and roads as smooth surfaces. For each polygon a triangular irregular network (TIN) is reconstructed and all polygons are 'stitched' together to form a closed DSM. An example of a section of this DSM is shown in Figure 2.3. The result of this process should be error-free DSM, that contains no intersection triangles, has no holes (so the surface is watertight) and where buildings are integrated into the terrain. All features are classified as one of the following classes:

1. Building
2. Terrain
3. Road
4. Water
5. Forest
6. Bridge
7. Separation

The BGT is often used as data source for the 2D polygons (could be any 2D dataset) and the elevation is obtained from a point cloud (either LAS or LAZ). The source data for this point cloud is a combination of AHN3 and point derived from dense image matching. The output can be exported into different formats, 3dfier supports OBJ, CityJSON, CityGML and CSV file formats. An example of the output in CityGML can be seen in Figure 2.4. The output will be a valid 3D model, defined following the specifications of IMGeo 2.1.1. [https://github.com/tudelft3d/3dfier]

Figure 2.3: Section of 3D surface with different classes [Stoter et al., 2017a]

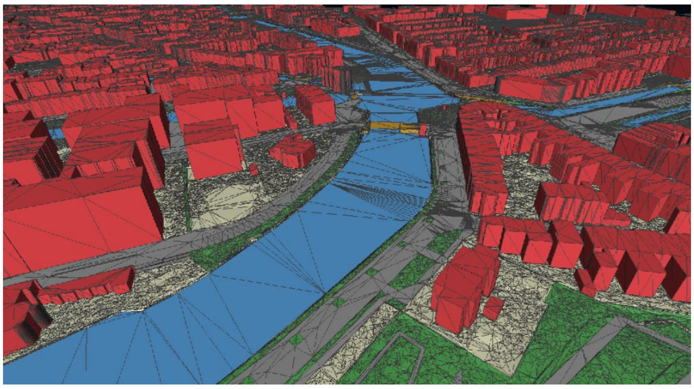


Figure 2.4: Result 3dfier output example in CityGML [Stoter et al., 2017a]

2.2.2 3D Standards and information models

Standards are essential during and after the development of 3D data. These standards describe the management, modelling, exchange and disclose of 3D geo-information. In Delft [2016] the developments of different 3D standards are examined, focusing on the standards that are relevant to the geo-domain. Among these standards are: GML, CityGML, gITF, KLM, InfraGML, IFC and SLPK. Borrmann et al. [2018] states that CityGML is one of the most important international standard used for 3D city models. This Section will elaborate on the two most used 3D standards during this research. The first one being CityGML and the second one CityJSON; a new JSON-based exchange format for the CityGML data model [Ledoux and Labetski, 2019].

CityGML

The CityGML standard is an comprehensive open data model and format for the storage and exchange of semantic 3D city models [Biljecki et al., 2018]. The standard defines multiple thematic concepts, such as: buildings, vegetation, water, land use and city furniture. These concepts can be distinguished at both a geometric as well as a semantic level (see 2.5). These different concept are described in CityGML's thematic modules and conceptually defined in Unified Modeling Language (UML) diagrams. The standard is based on Extensible Markup Language (XML) encoding, schema's can be found in the XMD files. CityGML is also based on Geography Markup Language (GML) (version 3.0), which is the exhange format used for geo-information (NEN3610) and defines how to handle and manage geometries.The CityGML standard is used worldwide, in a variety of application domains. While the models aims to be application-independent, the huge amount of different applications often require additional information to be implemented in the CityGML model [Biljecki et al., 2018]. It is possible to extend the CityGML model by using ADE's. These are also defined in Schema Definition Language (XSD) files and allow objects and attributes to be added to the model. Another characteristic feature of CityGML is the support of level of detail per object. [Kolbe et al., 2012]

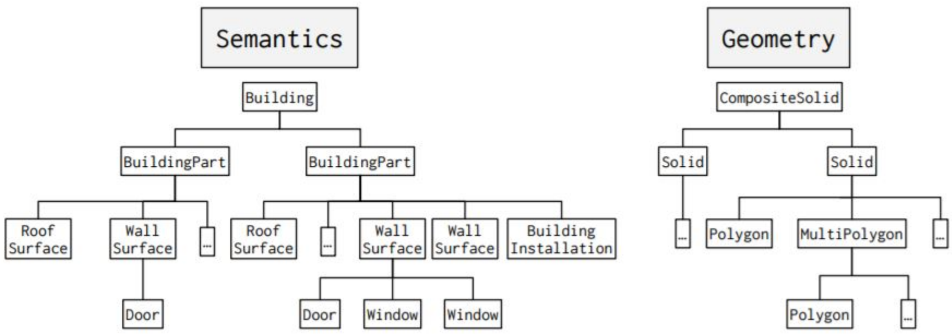


Figure 2.5: A building decomposed by semantics and geometry [Ledoux and Labetski, 2019]

An important concept in the CityGML standard is the use of LOD (Level of Detail). Five different level of detail are defined as shown in Figure 2.6. In this thesis research LOD will be mentioned several times, referring to CityGML LOD's. The concept of LOD is defined in CityGML 2.0 standard from Open Geospatial Consortium (OGC). This concept is primarily focused on buildings, but also intended for other thematic objects. In brief, the higher the LOD, the more the geometry and semantic complexity of an object increases. The need of different levels of detail, arises from the different application requirements and the different data collection processes. LOD also facilitates efficient visualisation and data analysis.

It is possible for an object to be stored multiple times in the same model, each one in a different LOD. The lowest level is represented by LOD0, in which the terrain is visualised as a 2.5D DTM and buildings as polygons (from either footprint or roof edges). In LOD1 the buildings are represented as simple building blocks, where all roofs are flat. In LOD2 the buildings the roofs are structured and all boundary surfaces have been thematically implemented. This means wall, roof and ground elements have also been defined separately. In LOD3, also interior structures are added to the buildings (windows, chimneys etc). The most detailed level is LOD4, where also objects inside of the buildings (stairs, furniture etc.) have been added, possibly with textures. [Kolbe et al., 2012]

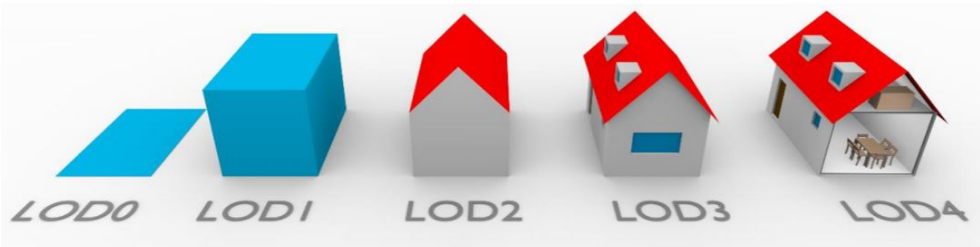


Figure 2.6: CityGML LOD's 0-4 [Delft, 2016]

CityGML has been developed by Special Interest Group 3D (SIG 3D), starting in 2002. Over 70 companies, municipalities and research institutions are a part of this group and have been working on the developments of interoperable 3D city models. The CityGML standard (version 1.0.0) is defined as an OGC standard since 2008. Since then the use of the 3D standard increased worldwide. Nowadays CityGML is used mostly across Europe, Canada, the Middle East and Asia. CityGML also played a big role in the 3D pilot, as described in Section 2.1.3, where a 3D geo-information standard and 3D infrastructure for Th Netherlands was obtained. [Kolbe et al., 2012] Since then the standard has developed, leading to CityGML 2.0 in 2011. Also new ideas and improvements of this version have been expressed, leaning towards CityGML 3.0. The CityGML 3.0 GML Encoding Specification is supposed to be published in 2019, while the Conceptual Model is already available at `https://github.com/opengeospatial/CityGML-3.0CM`.

As previously stated, the CityGML model is decomposed in different objects (or classes). CityGML has a core module and has several extension modules. All of these modules have their own XML schema file, each defining a globally unique XML namespace. In the CityGML files, the module namespaces all have associating prefixes. A list of the different modules, their corresponding XML and prefixes, are shown in Figure 2.7.

CityGML module	Namespace identifier	Namespace prefix
CityGML Core	http://www.opengis.net/citygml/2.0	core
Appearance	http://www.opengis.net/citygml/appearance/2.0	app
Bridge	http://www.opengis.net/citygml/bridge/2.0	brid
Building	http://www.opengis.net/citygml/building/2.0	bldg
CityFurniture	http://www.opengis.net/citygml/cityfurniture/2.0	frn
CityObjectGroup	http://www.opengis.net/citygml/cityobjectgroup/2.0	grp
Generics	http://www.opengis.net/citygml/generics/2.0	gen
LandUse	http://www.opengis.net/citygml/landuse/2.0	luse
Relief	http://www.opengis.net/citygml/relief/2.0	dem
Transportation	http://www.opengis.net/citygml/transportation/2.0	tran
Tunnel	http://www.opengis.net/citygml/tunnel/2.0	tun
Vegetation	http://www.opengis.net/citygml/vegetation/2.0	veg
WaterBody	http://www.opengis.net/citygml/waterbody/2.0	wtr
TexturedSurface [deprecated]	http://www.opengis.net/citygml/texturedsurface/2.0	tex

Figure 2.7: List of CityGML modules, their associated XML namespace identifiers, and example namespace prefixes. [Kolbe et al., 2012]

IMGeo and CityGML

IMGeo is the Dutch information model that defines how to store and manage geo-information. The aim of this model is to support the national exchange of data. The first version of this model was established in 2007 and the second version in 2012. In this last version the information model of the BGT is included. This is the mandatory part of the IMGeo. The remaining part is the optional, functioning as an extension to the mandatory part. The optional part aims to support the exchange of data for uses cases that require additional information. For example, the materials of road parts can be stored as an extra attribute. The collection and management of this additional data is, in contrast to the BGT data, not mandatory for source holders. [van den Brink et al., 2013b]

IMGeo 2.0 also supports the exchange of large-scale topography in 3D. From this version on the information model is based on CityGML. This means that all objects in IMGeo are linked to the CityGML classes. [van den Brink et al., 2013b] The model is now semantically, geometrically and syntactically an ADE for CityGML. Software tools that support CityGML, thus also support IMGeo. [Blaauboer et al., 2017]

CityJSON

While CityGML is an official standard of OGC, another open standard data model based on CityGML2.0 has been developed. This standard is called CityJSON and is a JavaScript Object Notation (JSON)-based encoding. As stated by Ledoux and Labetski [2019], the use of a 3D standard based on XML and GML has a few drawbacks. Arguments were given to prove CityGML files are verbose, hierarchical, complex and not adapted to the web. Also a low amount of software tools is capable of working with CityGML. The 3D geo-information group at Delft University of Technology started developing the new model. The aim of CityJSON is to offer an open standard that is easy-to-use, developer-friendly and more compact. Specifications of CityJSON 1.0.1 can be found on `https://www.cityjson.org/specs/1.0.1/`.

The current version of CityJSON includes almost all modules and characteristics of CityGML. Some of the features are left out, simply because they are seldom used, or because they would complicate the JSON encoding. For example, in CityGML the buildings as well as their primitive geometry can have an identifier (ID) (gml:id), while CityJSON only allows ID's on objects and semantics. CityJSON is able to store the geometry and semantics of an object and also distinguishes different levels of detail. A big difference with CityGML files can be found in the hierarchy within the data. In CityJSON files the storage is simplified by 'flatting' out the hierarchy as can be seen in CityGML files. Instead of using a hierarchy, different levels have been implemented, which are added to each object (see Figure 2.8). An example of a CityJSON file containing objects with different levels (thus, 'parent' and 'children' object) is shown in Figure 2.9. It is also possible to use and create extensions for CityJSON, in order to add new objects. [Ledoux and Labetski, 2019]

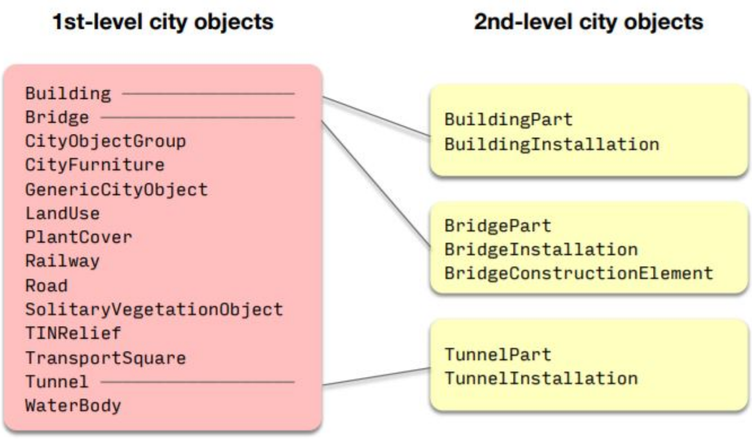


Figure 2.8: The implemented CityJSON classes (same name as CityGML classes) are divided into 1st and 2nd levels. [Ledoux and Labetski, 2019]

```
"CityObjects": {
  "id-1": {
    "type": "Building",
    "geographicalExtent": [ 84710.1, 446846.0, -5.3, 84757.1, 446944.0, 40.9 ],
    "attributes": {
      "measuredHeight": 22.3,
      "roofType": "gable",
      "owner": "Elvis Presley"
    },
    "children": ["id-2"],
    "geometry": [{...}]
  },
  "id-2": {
    "type": "BuildingPart",
    "parents": ["id-1"],
    "children": ["id-3"],
    ...
  },
  "id-3": {
    "type": "BuildingInstallation",
    "parents": ["id-2"],
    ...
  },
  "id-4": {
    "type": "LandUse",
    ...
  }
}
```

Figure 2.9: CityJSON code containing objects with different levels.[From: https://cityjson.org/specs/1.0.1/

2.3 USE CASES 3D CITY MODELS

2.3.1 Study Use Cases

As mentioned by Stoter et al. [2017b], the potential in using 3D geo-information in a variety of application increases, since the amount of available 3D data is growing. The value of this topographic data, for both 2D as well as 3D, is often measured in terms of usability [Sliuzas and Brussel, 2000]. Shiode [2012] states that as of March 2000, over 60 projects worldwide are developing (part of) a city in 3D. Many researches have been dedicated to this topic and take up an increasingly and wide variety number of domains. Studies like this could be very useful for stakeholders and public organisations, in order to create support for 3D developments and understand the market. Besides a wide variety of applications, also the group of users is very heterogeneous. These different users implement the 3D city models into their applications and/or develop the data themselves. The users can be found in both private and public sector and can be either professional or commercial. [Shiode, 2012]

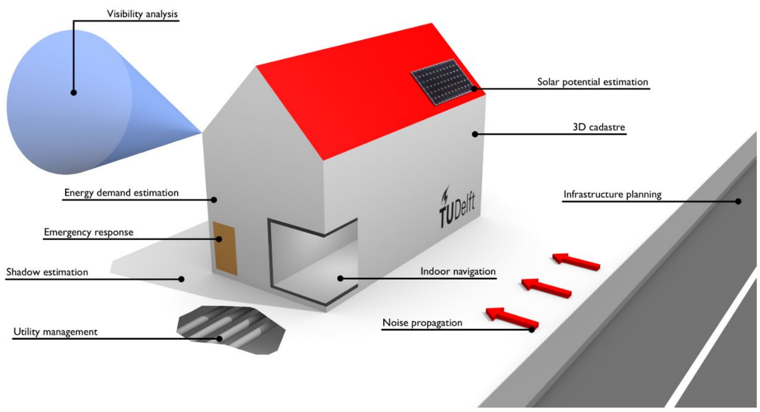


Figure 2.10: 3D city models applications in a variety of domains. [Biljecki et al., 2015]

Examples of 3D users, as stated by Shiode [2012], are: urban and rural planners, environmental agencies, telecommunications and utility companies, consultants, surveyors, architects and engineers. The study of Shiode [2012] distinguished four categories for the use of the 3D city models. The first category is planning and design, the second infrastructure and facility services, the third commercial sector and marketing and the fourth promotion and learning of information on cities. The study concludes that two movements towards 3D city models can be seen. The first one is that the growing amount of available 3D city models creates an increasing amount of application, thus more specific demand will be required. On the other hand, the need for 3D standardisation is rising, in order to improve compatibility and exchange of 3D data. [Shiode, 2012]

A more recent and comprehensive study regarding the utilisation of 3D city models is done by Biljecki et al. [2015]. The study mentions many challenges regarding the definition of use cases. By segmenting and categorising diverse use cases, the result is a list of use cases and applications. This list distinguishes two groups: non-visualisation based and visualisation-based use cases. Since the amount of use cases that rely on visualisation is larger than the other group, it can be stated that visualisation is an indispensable element in the development of 3D city models. [Biljecki et al., 2015]

2.3.2 Study 3D city models in Finland

Quite recently a research has been done on 3D city models of six cities in Finland. This study, published by Julin et al. [2018], examines different 3D city models and the expectations towards their use cases. The 3D models where provided by a variety of stakeholders, both public and private, for six cities in Finland: Espoo, Helsinki, Oulu, Tampere, Turku, and Vantaa. The study is done by means of data comparison and interviews with the stakeholders. The outcome could be of relevance to this thesis research. The main research questions differ, however, the methodologies are quite similar as they both involve interaction with a few big municipalities. The study in Finland distinguishes three main domains where 3D city models are applied. The first domain contains the professional GIS/CAD tools and use cases. This domain is mostly aimed at professional user, such as city planners, architects, surveyors etc. The second domain contains the virtual globes (3D web viewers), such as Google Earth, Google LLC and Mountain View. The use of 3D city models in this domain is aiming a user-friendly and web-based systems, targeting public audiences. The third domain contains the 3D game engines, which requires the highest visually realistic models (compared to the other domains). The use of the 3D models is focused on an interactive user experience. In contrast to the first and second domain, 3D city models in game engines are mostly not tied to geographic coordinate systems. [Julin et al., 2018]

The second part of the research included interviews with the stakeholders, whom were both public and private organisations. During the interviews the stakeholders stated some of the barriers concerning the development of an 3D city model. An overview of the results from the interviews is listed below:

- A lack of coordination and leadership within the organisation.
- The stakeholders all exist of groups of users with varying needs, expectations and views towards 3D city modelling.
- Legislation was not up to date.
- Certain issues as copyright, data ownership and privacy issues were unclear.
- The lack of expertise was seen to result in an incapacity to recognise the need for 3D and hence define the requirements of this data.
- The cities wanted to be less dependent on private contractors and consultants and have a more profound role. They preferred to generate and manage the 3D city models themselves, in order to support other companies that can implement the data into their own applications. [Julin et al., 2018]

In the end the study states a contradiction between the 3D city models and their expectations can be found, as they do not reach the envisioned variety of applications. A concept for the harmonising of 3D city models within the three defined domains is the end result (see Figure 2.11). The concept portrays a 3D spatial information infrastructure that focuses on different data sources: spatial data, non-spatial data and Building Information Model (BIM) data. [Julin et al., 2018]

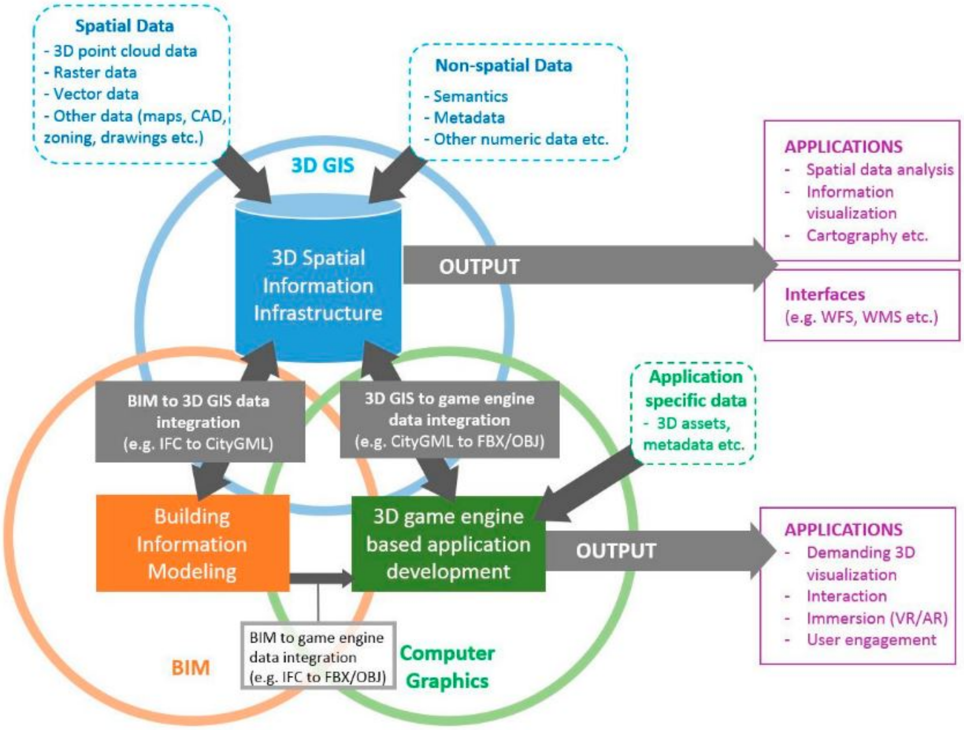


Figure 2.11: The concept for harmonising 3D city modelling. [Julin et al., 2018]

2.4 VALUE 3D CITY MODELS

2.4.1 Economical value

Other studies have been carried out to examine the value of 3D geo-information in means of economical benefits. On of these studies is published by Wong [2015]. This report demonstrates that the characteristics of 3D geo-information as an economic good must be considered during valuation and that the value of 3D geo-information is highly context dependent. The study states that the development of 3D geo-information involves different phases and groups of people, referred to as the value chain. In each step of this chain economic value can be produced. The three main groups of this chain are: consumers, businesses and government organisations. As their benefits grow, this could also have a positive impact on the public and economy. Further research to economic value of 3D geo-information requires that all the links within the 3D geo-information ecosystem to be identified. The industry is complex and there are a lot of horizontal and vertical links between companies in the value chain. The research can also be improved with further examination of the different users' needs and possible applications. [Wong, 2015]

2.4.2 Public value

Ho et al. [2018] states: "However, broader public management literature has shown that while economic value is vital for justifying public investment, it is not the only driving factor and that the creation of public value is crucially and equally significant as it conveys social and political legitimacy." A study has been carried out which describes how the use of 3D geo-information may potentially manifest as different types of public value. The increasing amount of 3D geo-information has led to a growing interest in public sector investments in this domain. Another cost-benefit analysis has been done on the data of 11 European Public Mapping Agency (PMA)'s. This study has used their data in order to examine the public value instead of the economical value. The outcome of the results show different types of public value that can potentially manifest from 3D geo-information. The use 3D geo-information led to increased quality of the citizens' lives, because they were able to provide advanced analysis on the 3D data. The outcomes also showed a greater transparency, confidence and better communication from governmental organisations towards to community. According to the study this resulted in greater trust in public organisations. [Ho et al., 2018]

3 METHODOLOGY

This Chapter will describe the methodology that is implemented during this thesis. The methodology is developed in order to formulate an answer to the main research question: *'How can a variety of 3D city models be integrated in a country wide covering 3D basemap based on large-scale topography?'*. The methodology has been split up into three components, as shown in Figure 3.1. These three components are coherent and related to each other, throughout the research. The first component involves a literature study (Chapter 2), to examine the state of art of 3D city models, their standards and information models and the different user needs and applications. Since a case study is done in the Netherlands, also the Dutch developments of large-scale topography are examined. In order to achieve deeper insides of the stakeholders needs and wishes, the second component has been included in the methodology. This component, which involved the interaction with stakeholders, will be further explained in Section 3.1. The third component involves the technical part of this thesis, where actual 3D city models are collected, compared and merged. A detailed description of this component is given in Section 3.2. The results of all three components are used to formulate an answer to the main research question.

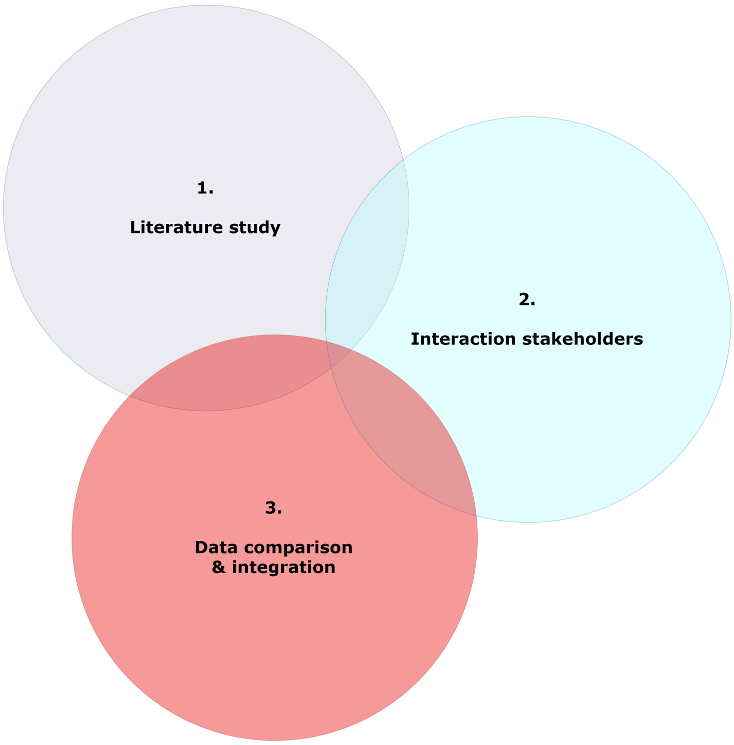


Figure 3.1: 3 components of the methodology

3.1 INTERACTION STAKEHOLDERS

3.1.1 Overview stakeholders

The second component of the methodology of this research contains the interaction with stakeholders, in order to obtain insights into the requirements according to the stakeholders. Not only the technical aspects, but also the role and needs of the stakeholders have to be taken into account during the research. During this research six stakeholders are involved that are or have been generating 3D models. The first stakeholder is Kadaster, which is the Dutch Cadastre, the National Mapping Agency (NMA) in The Netherlands. The other five stakeholders are all source-holders of the large-scale topography data in The Netherlands, including both a province as well as municipalities. These stakeholders are involved in the research, since they already experimented with the generation of 3D city models. Thus they are able to provide helpful resources, such as: 3D data, inside information about the wishes and needs of the organisation concerning 3D and feedback about their development processes.

Stakeholder	Contact person(s)
Kadaster	Vincent van Altena, Marc Post, Tony Baving
Province Noord-Brabant	Stefan van Gerwen
Municipality of Amsterdam	Wietse Balster
Municipality of The Hague	Isabella Tonioli, Kim Langenberg
Municipality of Eindhoven	Heidi van der Vloet, Mieke Pol, Mark Stals
Municipality of Rotterdam	Timo Erinkveld, Christian Wisse, Erik Jansen

Figure 3.2: List of stakeholders and contact persons

Figure 3.3: Involved stakeholders

3.1.2 Surveys

In order to get more insights of the processes within the stakeholders organisations and their 3D data, a survey had been sent out in the first phase of the study. The surveys included questions to get a better understanding of the data, and distinguishes four categories: contents, collection, management and actuality. The questions from the survey are listed in Figure 3.4.

Topic	Question
Contents	Does the data contain other objects besides buildings? If yes, what objects?
Collection	What is the source data for the footprints of the objects in the 3D model?
	What is the source data for the generation of height values in the 3D model?
	Is any additional source data used for other purposes?
	Is the model fully or party automatically generated?
	Is the generation of the 3D model done within the organisation or is it outsourced?
Management	Who (which team/group) manages the data?
	Is the data being managed and actualised?
	What database/software is used to manage and store the data?
	What is the standard 3D format of the data within the organisation?
	Is it possible to export to other 3D formats?
Actuality	When was the first version of the 3D model generated?
	How often is or will the model be updated?
	Will the update cover the full model or only the mutated parts?

Figure 3.4: Survey questions

3.1.3 Interviews

After the surveys had been send out, interviews with the stakeholders were planned. The aim of these interviews was to discuss and further examine the 3D developments within the organisation. Another goal was to get a better understanding of the needs and requirements from the stakeholders perspective. As Chapter 2 stated, a lot of studies have been done on the different use cases, requirements and applications of 3D data. However, few research has been done on the needs and requirements of the producers (the stakeholders in this research) of the 3D data. The different topics that are discussed during the meetings, are: data contents, management, actuality, distribution, barriers/challenges, purposes/usability and the needs and requirements for future developments.

In the last phase of the thesis research, the second meetings with the stakeholders took place. The research, including the results, were presented to them in order to get feedback. This feedback is processed in the discussion of Chapter 6.

3.2 DATA COMPARISON AND INTEGRATION

3.2.1 Collection and comparison of data

The third component of the methodology contains the comparing and integration of the different 3D test data. The test data is located in five places: Eindhoven, The Hague, Rotterdam, Amsterdam Baarle-Nassau. For each of these locations an associating CityGML model is generated by Kadaster. The first step is to examine all specifications and compare the different 3D models. The data will be compared to each other, both geometrically and semantically. The following specifications of the data will be described or visualised:

- File format
- Version
- CRS
- Level of detail
- Geometry
- Attributes
- Coverage

3.2.2 Integration of data

The specification description of the data is needed for the further construction of the methodology; the integration of the different 3D models. The proposed workflow of this integration depends heavily on the input data. The main goal of this data integration, is the experience and examination of all the encounters and barriers during this process. Once the integrated models have been generated, further analysis can be performed. Examples of these analysis are: 2D footprints, 3D building heights, terrain height and connectivity building and terrain. The workflow that is developed to integrate the data, depends on the test data and the available tools and methods. Specifications of this test data and the suitable tools and methods, are described in the next chapter.

4 IMPLEMENTATION & EXPERIMENTS

This chapter will elaborate on the implementation details of the methodology. First the datasets and tools will be described in Section 4.1. This includes an overview of the datasets from the stakeholders involved, concerning their formatting and contents. This overview is given in Section 4.1.1. The different software that is used during the implementation will be described and discussed in Section 4.1.2. Secondly the implementation of the methodology proposed in Chapter 3 will be described in Section 4.2. Experiments during this implementation phase will be further described in Section 4.3.

4.1 TOOLS AND DATASETS

4.1.1 Datasets

During the research a case study has been done in the Netherlands, involving six stakeholders that are or have been developing 3D models. Sections of these 3D models will be used in this study and the workflow methods have been developed based on the test data. The resulted workflow methods are described in Chapter 5. The implementation, analysis and results of the application of these methods heavily depend on the formatting, source, encoding and contents of the datasets. Therefor, a detailed overview of the different datasets will be given in this section. One of the stakeholders is Kadaster, whom generated CityGML models for all five locations shown in Figure 4.1. The models are generated with 3dfier [https://github.com/tudelft3d/3dfier] and each contain a subunit of 1000x1250 meter. Figure 4.2 shows an overview of their contents.

Figure 4.1: Location datasets Kadaster

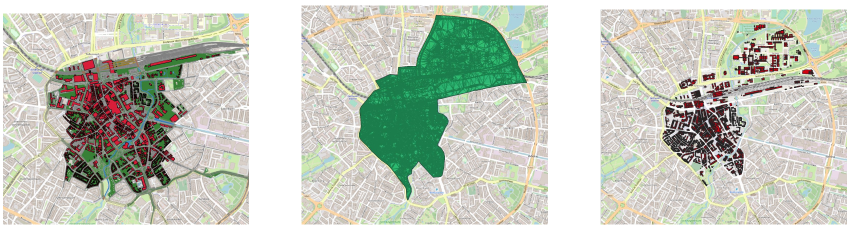
	Kadaster					
Format	CityGML					
Version	2.0					
System	EPSG:7415					
		File1 Amsterdam	File 2 The Hague	File 3 Eindhoven	File 4 Noord-Brabant	File 5 Rotterdam
Features	Bridge:	173	61	75	2	32
	Building:	3523	2468	2531	89	3387
	CityModel:	1	1	1	1	1
	GenericCityObject:	341	51	264	0	142
	LandUse:	17295	8685	5242	619	7949
	PlantCover:	30	992	1041	151	1169
	Road:	2858	2599	2975	154	4015
	WaterBody:	104	38	43	170	23

Figure 4.2: Overview datasets from Kadaster

The second stakeholder is the Municipality of Eindhoven. They have provided two CityGML datasets, one containing the terrain and one containing buildings in LOD3. An overview of their contents in shown in Figure 4.3 and their location compared to the data from Kadaster is shown in Figure 4.4.

	Municipality of Eindhoven		
Format	CityGML		
Version	1.0		
System	EPSG:28992		
		File 1 (Buildings)	File 2 (Terrain)
Features	Building:	11350	0
	CityModel:	1	1
	GenericCityObject:	0	140607

Figure 4.3: Overview datasets from Eindhoven



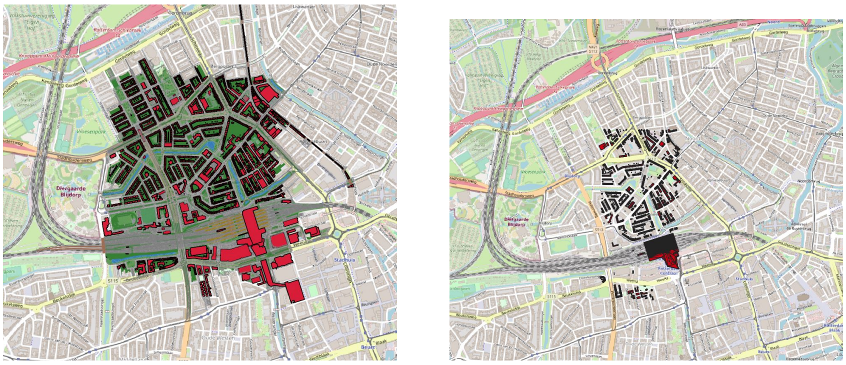
(a) (b) (c)

Figure 4.4: Location datasets Eindhoven from: (a) Kadaster (b) Municipality Eindhoven terrain (c) Municipality Eindhoven buildings.

The third stakeholder is the Municipality of Rotterdam, who has a 3D city model available at https://www.3drotterdam.nl/#/. A section of choice can be exported to a variety of 3D file formats. For this study a dataset containing buildings in LOD2 is downloaded in CityGML, as shown in Figure 4.5. The location of this dataset compared to the location of Kadaster is shown in Figure 4.6.

Municipality of Rotterdam		
Format	CityGML	
Version	1.0	
System	EPSG:28992	
		File 1 (Buildings)
Features	Building:	1744
	CityModel:	1

Figure 4.5: Overview datasets from Rotterdam



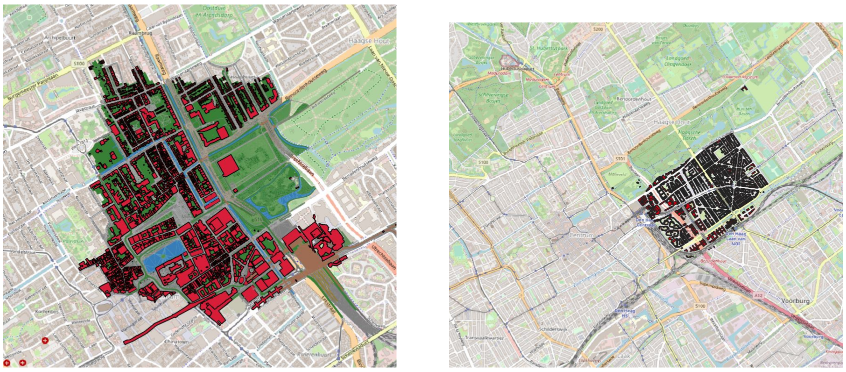
(a) (b)

Figure 4.6: Location datasets Rotterdam from: (a) Kadaster (b) Municipality Rotterdam buildings.

The fourth stakeholder is the Municipality of Den Haag, who has a 3D city model available at https://www.nederlandin3d.nl/denhaag/#/. A neighbourhood of choice in CityGML format can be downloaded from their data platform (https://denhaag.dataplatform.nl/#/data). The contents of the downloaded neighbourhoods are shown in Figure 4.7. The location of this dataset compared to the location of Kadaster is shown in Figure 4.8.

Municipality of The Hague		
Format	CityGML	
Version	1.0	
System	EPSG:28992	
		File 1 (Buildings)
Features	Building:	4203
	CityModel:	1

Figure 4.7: Overview datasets from Den Haag



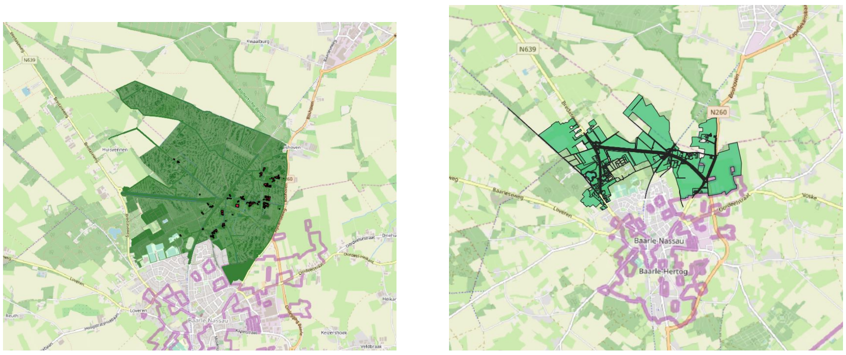
(a) (b)

Figure 4.8: Location datasets Den Haag from: (a) Kadaster (b) Municipality Den Haag buildings.

The fifth stakeholder is the Province Noord-Brabant. This stakeholder provided an Environmental Systems Research Institute (ESRI) shapefile containing the terrain, located in Baarle-Nassau. An overview of the contents is given in Figure 4.9 and the location compared to the data of Kadaster is shown in Figure 4.10.

	Province of North-Brabant	
Format	ESRI Shapefile	
Version	-	
System	EPSG:28992	
		File 1 (Terrain)
Features	Polygon:	914

Figure 4.9: Overview datasets from Noord-Brabant



(a) (b)

Figure 4.10: Location datasets Noord-Brabant from: (a) Kadaster (b) Province Noord-Brabant

4.1.2 Software

A variety of tools and software will be used during this research. In this section an overview of these software is given. These different software programs are used to analyse, visualise, compare, convert, manipulate and validate the datasets.

- *cjio*
  Cjio is a Python command-line interface (CLI) program, used for the processing, validation and manipulation of CityJSON files. The operators, among other things, include: validation, merging, changing coordinate system and exporting to other formats. Multiple operations can be chained in one command, creating one final file. [https://github.com/tudelft3d/cjio]
- *citygml4j*
  Citygml4j is an open-source Java class library and application programming interface (API), created in order to facilitate the reading, writing and manipulation of CityGML files. Starting from version 2.6.0, citygml4j supports parsing and writing CityJSON, a format for encoding a subset of the CityGML data model using JSON instead of GML. [https://github.com/citygml4j/citygml4j]
- *FME Workbench*
  This software is the primary Feature Manipulation Engine (FME) desktop application for translating and transforming data. For this thesis the visual workflow editor is used for the conversion, manipulation and analysing of data. [https://www.safe.com/fme/fme-desktop/]
- *QGIS*
  QGIS a is free and open-source geographical information system (GIS), created in order to create, edit, visualise, analyse and publish geospatial information. [qgis.org/en/site/]
- *CityJSON loader plugin*
  This is a Python plugin for QGIS 3 which adds support for loading CityJSON datasets in QGIS. The city objects are loaded as features in layers, visualisation is possible in both 2D as well as 3D. [https://github.com/tudelft3d/cityjson-qgis-plugin]
- *LandXplorer*
  LandXplorer CityGML Viewer is an interactive, real-time visualization system, that allows you to effectively load, explore, and edit large 3D city models based on CityGML. [http://download.autodesk.com/us/landxplorer/docs/ldx_citygml_viewer/html/index.html?topic.htm]
- *Meshlab*
  Meshlab is an open source system for the processing and editing of 3D meshes. For this thesis the software is used to analyse and visualize the 3D city models in OBJ format. [http://www.meshlab.net/]
- *Google Earth Pro*
  An interactive 3D program, used for the visualisation of the data in the real world. [https://google-earth-pro.nl.softonic.com/]
- *CityJSON viewer*
  An online viewer that allows you to drag, drop and visualise CityJSON data. [https://github.com/fhb1990/CityJSON-viewer]
- *val3dity*
  A validator that verifies whether a 3D primitive respects the definition as given in ISO19107 and GML/CityGML. Written in C++. [https://github.com/tudelft3d/]

4.2 IMPLEMENTATION

This section will elaborate on the implementation of the methodology described in Chapter 3. This methodology exists of three components: a literature study, interaction with stakeholders and the data integration. The results of the first component, the literature study, can be found in Chapter 2. During this phase it became clear that many studies have been carried out to examine the use and purposes of 3D, but not the wishes and role of stakeholders. In order to get more insights on these topics, interviews and surveys with the stakeholders have been carried out. The results of these surveys and interviews can be found in Chapter 5. The implementation of the third component, the comparison and integration of data, will be further described in this section.

4.2.1 Conversion to CityJSON

The first step in the methodology is to convert all files, from both Kadaster and the 3D source holders, to CityJSON files. This conversion is done using the citygml4j program, which has an 'citygml2cityjson' included. This package reads a CityGML file as input, converts it and writes the data to an CityJSON file. During the conversion, the process encountered a few errors that had to be taken care of. These are described in the following subsections.

Invalid CityGML caused by XML entity
One of the CityGML files from Kadaster was disrupted during the conversion to CityJSON. After a validation check with val3dity, the file turned out to be invalid. The error during the conversion was caused by the ampersand sign, which was found in the values of the generic attribute, as shown in Figure 4.11. The ampersand is one of the XML entities and is in this process handled as the start of an entity. Should these entities occur in a name of an attribute, the sign should be written as their escape facility. [Van Muylem, 2013] After changing the ampersand signs to `\amp;`, which is the escape facility for an ampersand sign, the file was valid and did not disturb the conversion to CityJSON anymore.

```
<gen:stringAttribute name="documentnummer"><gen:value>10B&W0006</gen:value>
```

Figure 4.11: Ampersand in Generic Attribute

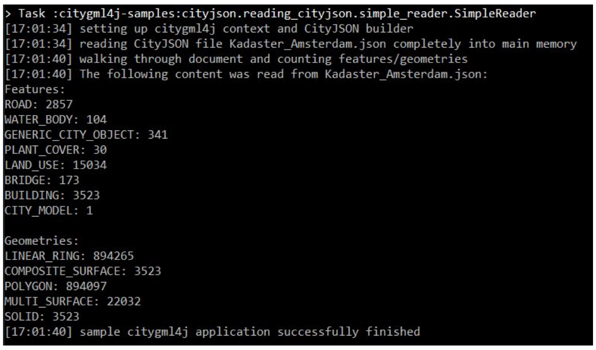
Error reading *measureAttribute*
Another error occurred during the conversion to CityGML, in which the process seemed to have trouble reading the measureAttribute. The conversion does work when this attribute is either deleted or when the schema link (Figure 4.12 is changed to version 1 instead of 2. After consulting the owner of citygml4j (Claus Nagel), this turned out to be a bug in the program. A new version of the program was uploaded and the conversion to cityJSON was successfully executed.

```
xmlns:gen="http://www.opengis.net/citygml/generics/2.0"
```

Figure 4.12: Schema link to generics 2.0

PlantCover features twice in CityGML

The PlantCover features are all found twice in CityGML files of Kadaster. After conversion to CityJSON all the doubles are automatically removed, since a feature with a unique ID can only be converted once with citygml4j. In Figure 4.13 is the contents of Kadaster's CityJSON file of Amsterdam shown. In the original CityGML file 60 PlantCover features were found, while only the 30 unique features are converted to CityJSON.



```
> Task :citygml4j-samples:cityjson.reading_cityjson.simple_reader.SimpleReader
[17:01:34] setting up citygml4j context and CityJSON builder
[17:01:34] reading CityJSON file Kadaster_Amsterdam.json completely into main memory
[17:01:40] walking through document and counting features/geometries
[17:01:40] The following content was read from Kadaster_Amsterdam.json:
Features:
ROAD: 2857
WATER_BODY: 104
GENERIC_CITY_OBJECT: 341
PLANT_COVER: 30
LAND_USE: 15034
BRIDGE: 173
BUILDING: 3523
CITY_MODEL: 1

Geometries:
LINEAR_RING: 894265
COMPOSITE_SURFACE: 3523
POLYGON: 894097
MULTI_SURFACE: 22032
SOLID: 3523
[17:01:40] sample citygml4j application successfully finished
```

Figure 4.13: Contents CityJSON Amsterdam (command executed with citygml4j)

Missing LandUse features after conversion

In Figure 4.13 it is also noticeable that the amount of LandUse features (15034) does not match the amount in the original CityGML file (17295) as reported in Figure 4.2. It turned out that after the conversion a random amount of LandUse features was missing in all the CityJSON files from the Kadaster. After visual inspection of the CityJSON file in QGIS, it can be concluded that all missing LandUse features are the features below buildings (see Figure 4.14). After checking the original CityGML code, it became clear that the missing LandUse features (mistakenly) got the same ID as the building on top of it. During the conversion citygml4j converts features with a unique ID only once, thus in this case leaving out some of the LandUse features. This problem is reported to Kadaster and could be solved in the code of 3dfier, which could create different ID's for the buildings and LandUse feateres. Otherwise the problem can be solved by splitting the buildings and the terrain features before the conversion to CityJSON.

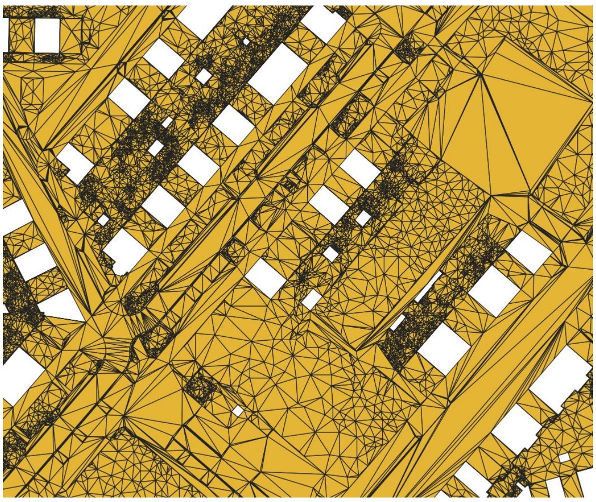


Figure 4.14: Missing LandUse features in CityJSON Amsterdam

4.2.2 Setting the coordinate system

The second step of the methodology was to set the same coordinate system to all of the CityJSON files. In the specification of the datasets in Section 4.1.1 it is noticeable that the files have different coordinate systems, those from Kadaster EPSG:7415 and those from the other stakeholders EPSG:28992. Changing the coordinate system of these CityJSON files to EPSG:7415 is done with the *assign_epsg* command of cjio. During this process, it appeared the CityJSON files didn't have an EPSG assigned to them after the conversion from CityGML. This also seemed to be a bug in the code from citygml4j.

4.2.3 Merging of CityJSON files

The third step of the methodology contains the merging of the CityJSON file from Kadaster with the CityJSON file from the other stakeholders. This is done for all stakeholders whom provided 3D models, thus for the locations: Den Haag, Eindhoven, Rotterdam and Baarle-Nassau (Noord-Brabant). Cjio command line interface is used to first filter out the buildings from the Kadaster files, leaving all feature types except for the buildings. The next step is to merge these features with the buildings of the other stakeholder. Cjio allows these two steps to be chained, resulting in one command (see Figure 4.15). Since the municipality of Eindhoven also provided a dataset with the terrain (without buildings), the merging with the Kadaster file is also done vice versa. Resulting in one CityJSON file containing the buildings generated by Kadaster and the terrain generated by the municipality.

```
cjio file_1.json subset --cotype Building --exclude merge file_2.json save
file_3.json
```

Figure 4.15: Example cjio command using *subset* and *merge*

4.2.4 Conversion to CityGML and OBJ

The last steps of the methodology contain the conversion back to CityGML and to OBJ. Not a lot of software tools are suitable for the visualisation of CityGML and CityJSON, and the tools that are available mostly have difficulties processing big files. Though there are a lot of tools for the visualisation of OBJ files, regardless of the size. For this reason the conversion to OBJ is done, in order to further inspect and visualise the final results. The *cityjson2citygml* package from citygml4j is used for the conversion to CityGML. This process was for each file successfully completed in one go, resulting in valid CityGML files. The conversion from CityJSON to OBJ is executed with the cjio *export* command. This conversion also succeeds, though after a visual inspection of the data in the OBJ file from Eindhoven, the file seems compressed. Figure 4.16a shows a piece of the compressed OBJ, where the vertices are stored as integers. The conversion to OBJ is done a second time, where the *decompress* command is added. The output of the OBJ file looks good now, as shown in Figure 4.16b.

```
v 1688531 1153990 60879
v 1687531 1152990 60849
v 1689395 1150695 61010
v 1687031 1152490 60720
v 1688319 1150847 60940
...
```

(a)

```
v 161507.82799999998 382770.68799999997 16.579
v 161506.82799999998 382769.68799999997 16.549
v 161508.69199999998 382767.393 16.71
v 161506.32799999998 382769.18799999997 16.42
v 161507.61599999998 382767.545 16.64
...
```

(b)

Figure 4.16: Piece of code OBJ file: (a) Compressed (b) Decompressed

4.3 EXPERIMENTS

4.3.1 Comparison with different source data

Since multiple 3D models are available for the same locations, multiple comparison analysis on the geometry can be carried out. The first comparison has been done using the 2D footprints of buildings from four different data sources: (1) The CityGML generated by Kadaster (2) The CityGML generated by the associating stakeholder for that location (3) The BAG footprint and (4) The BGT footprint. A second analysis is done on the 3D models of the same buildings. The maximum height of the building and the terrain height will be compared for (1) The Kadaster building and (2) The building of the associating stakeholder. A third analysis will be done on the final integrated files, where the terrain of the Kadaster is merged with the buildings from the associating stakeholders.

4.3.2 Comparison terrain heights

Since the municipality of Eindhoven also provided a 3D terrain model, an experiment has been done on the height differences with the terrain heights from the Kadaster model. As proposed in Chapter 3, a FME workflow is implemented to retrieve the height values for both terrain models. The input grid is made for that same location, where points are in a grid of 2x2 m. This resulted in a grid of 174.390 points, containing the height values of both stakeholders. Thus, the difference between the heights can be calculated in order to perform multiple analysis. For example, the biggest height differences will show the locations where the data in one of the two models is not corresponding to the real heights. The results of these experiments will be described in Chapter 5.

5 RESULTS & ANALYSIS

This section will elaborate on the results of the surveys and structured interviews and give an analysis of the data. At first the results of the surveys will be described in Section 5.1. Secondly the results of the meetings with the stakeholders will be discussed in Section 5.2. In Section 5.3 the resulting workflow of the data integration is described. Section 5.4 elaborates on the results of the data, by means of visualisation and analysis.

5.1 RESULTS SURVEY

In the first phase of the thesis, a survey had been send to all stakeholders involved. The results of this survey have been divided in four categories: contents, source data, process and management & actuality. Figure 5.1 gives an overview of the different datasets based on these categories.

		Kadaster	Amsterdam	Den Haag	Eindhoven	Noord-Brabant	Rotterdam
Contents	Buildings LOD1	✓	✓				✓
	Buildings LOD2			✓			✓
	Buildings LOD3				✓		
	Terrain	✓	✓		✓	✓	✓
	Trees		✓	✓			✓
	Bridges, platforms etc.	✓				✓	✓
	Other objects						✓
Source Data	BAG	✓	✓	✓	✓		✓
	BGT	✓	✓		✓	✓	✓
	AHN2				✓		
	AHN3	✓	✓				
	Own point cloud	✓		✓	✓	✓	✓
	DigTop			✓			
Process	Fully automatic	✓	✓			✓	
	Partly automatic and partly manually			✓	✓		✓
Management & actuality	Managed	✓	✓	✓	✓	✓	✓
	Distributed			✓			✓
	Standard File Formats	CityGML	QM tiles OBJ FBX	CityGML	DNG FGDB CityGML	Shapefile	CityGML
	First version	2017	2019	2010	2013	<2000	2016
	Update frequency	Yearly	?	?	incidental	daily	incidental
	Fully updated or based on mutations	fully	fully	fully	based on mutations	based on mutations	based on mu-tations

Figure 5.1: Comparison data in four categories

Figure 5.2 gives an overview of the datasets specifications compared to each other. Noticeable is the big difference in the amount and type of the attributes. The attribute names of the Kadaster dataset are the same as the attributes from the original BGT features. Multiple equal attributes are present in the different datasets (for example *'identificatie'*), but have different attribute names (*'gebouwnummer'*, *'PandID'*).

	Kadaster	Eindhoven	Rotterdam	Den Haag	Noord-Brabant
Format	CityGML	CityGML	CityGML	CityGML	ESRI Shapefile
Version	2.0	1.0	1.0	1.0	-
System	EPSG:7415	EPSG:28992	EPSG:28992	EPSG:28992	EPSG:28992
Level of Detail	1	3	2	2	1
Geometries	MultiSurface Solid	MultiSurface Solid	Solid	MultiSurface	MultiSurface *after conversion to CityGML
Attributes	bgt_status, objectbegintijd, lokaalid, tijdstipregistratie, plus_status, eindregistratie, bronhouder, plus_type, identificatie, relatievehoogteligging, objectid, objecteindtijd, measuredHeight, lv_publicatiedatum, bgt_type, inonderzoek, Namespace Aanduidingrecordcorrectie, Aanduidingrecordinactief, Begindatumtijdvakgeldigheid, bouwjaar, Documentnummer, Documentdatum, Einddatumtijdvakgeldigheid, Identificatie, Inonderzoek, Min height surface, Min height units_surface, Objectid Pandstatus, Shape_area, Shape_lenght	measuredHeight	statusOmschr, gebouwnummer, creationDate, typeOmschr, yearOfConstruction, deviation, aantalBouwlagen, laagste_bouwlaag, avineonStatus, hoogste_bouwlaag	Model, Adressen, GoothgtNap, NokhgtNap, Maaiveld, Bouwjaar, NokhgtRel, Wijkcode, Bron, Wijknaam, GoothgtRel, Pandstatus, PandID	IMGEO_BEHE IMGEO_BRON IMGEO_INON IMGEO_KLAS IMGEO_LVPU IMGEO_SLEU IMGEO_TYPE IMGEO_TYP0 TEXT_DGDTW NIVO_DGDTW LOKAALID_D OBJECT_DGD CT_1IMGEO_ CK_1BEHEER CT_2IMGEO_ CK_2BRONHO CT_4IMGEO_ CK_4PARENT CT_7IMGEO_ CK_7PARENT CT_8IMGEO_ CK_8PARENT

Figure 5.2: Comparison data specifications

5.2 RESULTS MEETINGS

During the first phase of the thesis, right after the survey, the meetings with the stakeholders took place. The purposes of these meetings is to gain more insights of the use of 3D and the requirements and needs of the stakeholders. This section will elaborate on the findings of the meetings. In addition to these meetings, I also attended a 3D event organised by the municipality of Rotterdam. This event was attended by 15 municipalities that have been generating 3D models or are interested in the developments. Besides the big municipalities, also some of the smaller municipalities were present that day.

Organisation

The first thing to notice is the fact that every organisation is different in terms of departments and structure. Even though four of the stakeholders are municipalities, they all have a different team or project group working on or with the 3D data. This leads to groups of people with different backgrounds and a variety of knowledge about 3D geo-information. The different departments of the stakeholders include: team Geodesy, Urban Development department, team Geoservices and 3D project groups. One of the stakeholders expressed the wish to switch the management of the 3D model to the Geodata team, which is also responsible for the BAG and BGT. During the 3D event, it was mentioned a couple of times that some of the source holders lack enough knowledge of 3D and GIS within the organisation. It was also stated that not all stakeholders have enough public and financial support within their organisation. 3D is often seen as an (big) investment with unclear benefits. The question arose if the 3D movement should be initiated from bottom up or top down. Most of the stakeholders prefer the first approach. Though there should be more guidelines facilitated from higher up organisations, in order to achieve a consistency. The different point of views have lead to yet another valuable discussion, should an organisation lean towards a supply-oriented or a demand-driven approach? The surveyed stakeholders state expect that the demand and uses of 3D data definitely will increase. Though the use and applications can be found in a wide variety of domains, each one requiring different 3D data. For this reason among others, all stakeholders prefer the first approach.

Data specifications

The majority of the stakeholders has outsourced the generation of the 3D model to external companies. Though during the 3D event the need arose to take this upon their selves in the future. The biggest benefit of bringing in the knowledge within the organisation, is that they are no longer dependent on the external (technical) company. This would probably also lead to an improved exchange of 3D geo-information knowledge and data between stakeholders. When looking at the overview of the 3D models in Figure 5.2, it is noticeable that all stakeholders but one have used their own point clouds in order to retrieve height values. These point clouds are derived from photogrammetry and tachymetry. The reason for this is that the AHN point cloud is considered not detailed and accurate enough for the construction of 3D objects. All stakeholders have used the BAG footprints for the construction of the buildings.

Use of 3D model
During the meetings with the stakeholders, the following foreseen uses of 3D models where mentioned:

- Spatial Planning
- Simulations (traffic, water flooding, routing, shadow)
- Participation citizens in projects
- Analysis (noise, air quality)

Also some future national developments will increase the need for 3D data. Examples of these developments are asset-management, BIM and the Environment and Planning Act which will start in 2021. The current use of the 3D models varies per stakeholder. Some use the models within the organisation, others also made the data available as open data. The next question asked is about a 3D BGT model, should this be possible and necessary in the (nearby) future? Four of the stakeholders believe this should be the next step within the 3D developments. The other two stakeholder state that 3D models of topography will increase (and should), but that the construction of the 3D data should not be necessarily made obligated by higher authorities.

5.3 RESULTS WORKFLOW DATA INTEGRATION

5.3.1 Integration of data

Two different methods have been developed in order to generate integrated 3D models, containing both data from Kadaster and data of the other stakeholder for the associating location. The workflow of method 1 is illustrated in Figure 5.3, based on two CityGML input datasets. For each step the corresponding software tool is given. The second workflow is based on a CityGML and a shapefile input, which is shown in Figure 5.4. The main difference is the additional step, which is to convert the shapefile to a CityGML compliant file. The workflow for this conversion will be further described in Section 5.3.2.

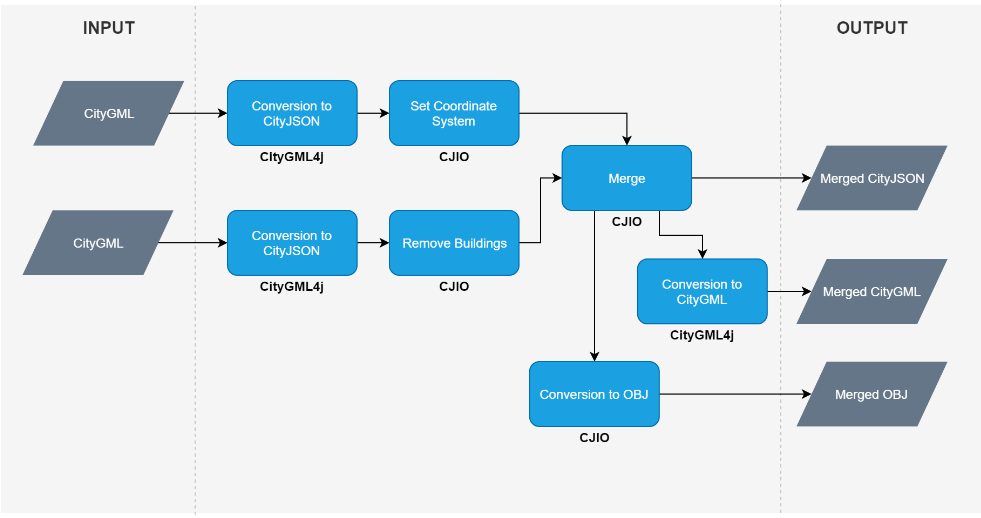


Figure 5.3: Workflow method 1

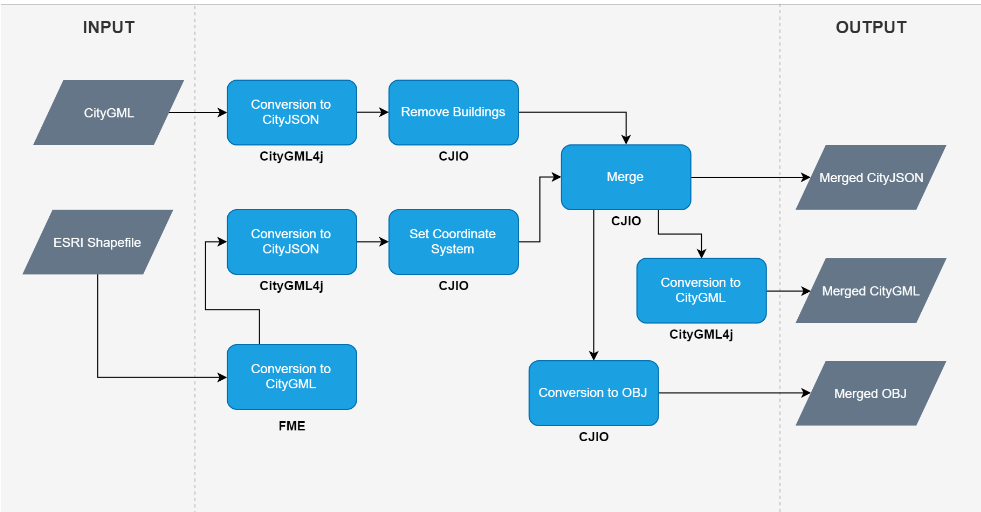


Figure 5.4: Workflow method 2

Both methods contain the following steps:

- **Step 1:** Conversion to CityJSON
- **Step 2:** Setting the coordinate system
- **Step 3:** Merging files
- **Step 4:** Conversion to CityGML
- **Step 5:** Conversion to OBJ

5.3.2 Workflow conversion shapefile to CityGML

This workflow method has been specifically made for the data of the Province of Noord-Brabant, whom provided their data in ESRI shapefile format. The workflow as illustrated in Figure 5.5 contains the following steps that can be implemented in FME software:

- **Step 1:** Attribute filter
  The first step is to filter out the different CityGML object. The objects in the data of Noord-Brabant all have an attribute called 'IMGeo klasse'. Each of these classes correspond to a certain CityGML class, an overview of the existing classes is shown in Figure 5.6.
- **Step 2:** Geometry Extractor
  This FME component extracts the geometry of a feature according to the setting of the geometry encoding parameter. In this case the encoding will be set on 'GML3.2.1'.
- **Step 3:** Geometry Replacer
  This FME component replaces the geometry of a feature according to the setting of the geometry encoding parameter. The geometry will be set on 'GML'.
- **Step 4:** Attribute Creator
  The next step is to add an attribute with the Attribute Creator. This attribute is called 'citygml_lod_name', since every object in CityGML needs to have a LOD specified. For PlantCover, for example, the value is set on 'lod1MultiSurface'.
- **Step 5:** Orientor
  This component is added in order to adjust the orientation of a the surfaces of the features.
- **Step 6:** Geometry Property Setter
  This FME component sets selected geometry names or traits from feature attributes or constants. In this case the attribute 'citygml_lod_name' is chosen as geometry.
- **Step 7:** Attribute Renamer
  Since the features in the original shapefile have their ID stored in the 'BGTID' attribute, this attribute will be renamed to the CityGML compliant 'gml_id' attribute.
- **Step 8:** Attribute Keeper
  This last step is added, in order to remove all the unnecessary attributes.

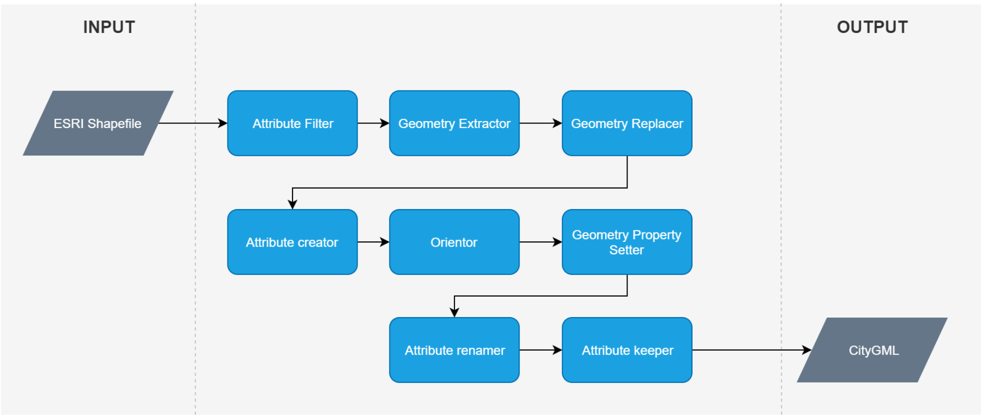


Figure 5.5: FME workflow shapefile to CityGML

IMGEO klasse	CityGML object
3	PlantCover
5	BuildingInstallation
8	GenericCityObject
12	BridgeConstruction
13	GenericCityObject
18	LandUse
19	Road
20	WaterBody
22	Building
24	GenericCityObject
31	Road
34	WaterBody

Figure 5.6: IMGeo classes with their associating CityGML object

5.3.3 Workflow terrain height analysis

One of the stakeholders, the municipality of Eindhoven, has also provided a 3D model of the terrain in CityGML. Since Kadaster also generated the terrain model for the same location, further analysis can be done on the both. In order to compare the terrain height in both model and perform additional analysis on the results, a new FME workflow has been constructed. This workflow is shown in Figure 5.7 and interpolates a grid of points on the terrain model to retrieve their height (Z) values. Thus, the workflow takes the terrain model as input, together with a grid of points. The output is the same shapefile containing the point grid, but the features have an additional attribute. The workflow contains the following steps.

- **Step 1:** Surface Draper
  The first step is to overlay the drape features (grid points) onto the surface model (terrain model). The points, modelled on the terrains' surface, are the output.

- **Step 2:** Geometry Extractor
  This FME component retrieves the value of the x, y, and z coordinate at the specified index into attributes. The Z-value is added as attribute.

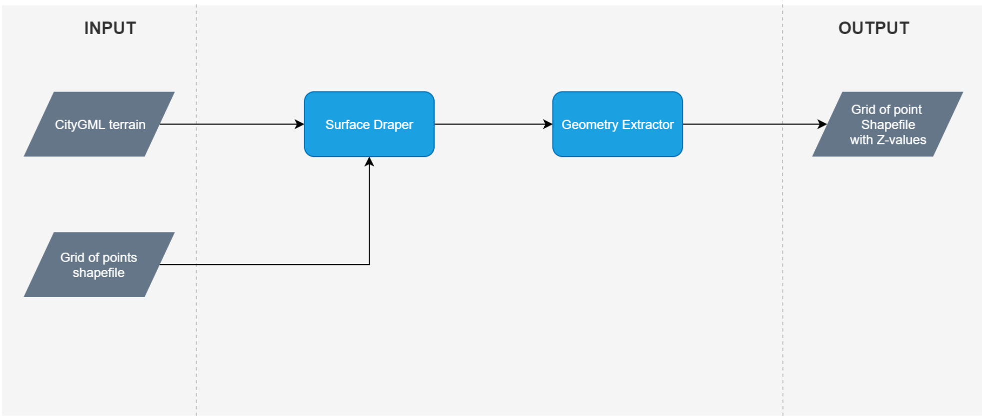


Figure 5.7: FME workflow draping a grid on a terrain model

5.4 RESULTS DATA

5.4.1 2D footprint comparison

In this section an analysis is done on the footprints of six buildings, which are shown in Figure 5.8. Each buildings footprint will be compared with the BAG, the BGT, the footprint in the Kadaster dataset and the footprint in the other stakeholders dataset. Figure 5.9 and 5.10 show the result of building 1 and 2 in Den Haag. In both cases the footprints of Kadaster are equal to the BAG and the footprints of the municipality of Den Haag do not match the BAG nor the BGT. Figure 5.11 and 5.12 show the result of the footprint comparison of two buildings in Rotterdam. The building footprints from both Kadaster and the municipality of Rotterdam are equal to the BAG footprint. Figure 5.13 and 5.14 show the result of the footprint comparison of two buildings in Eindhoven. For building 2 is it clearly visible the building footprint of the municipality does not match the footprint from the BAG. Building 1 seems to match the BAG on first sight, but a small difference between the two footprints can be noticed on the south east side of the building.

Figure 5.8: Google Earth view of test buildings

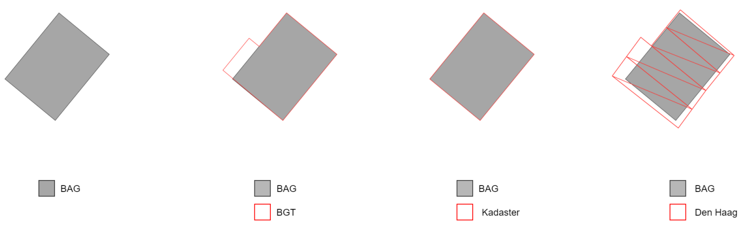


Figure 5.9: Den Haag building 1 footprints

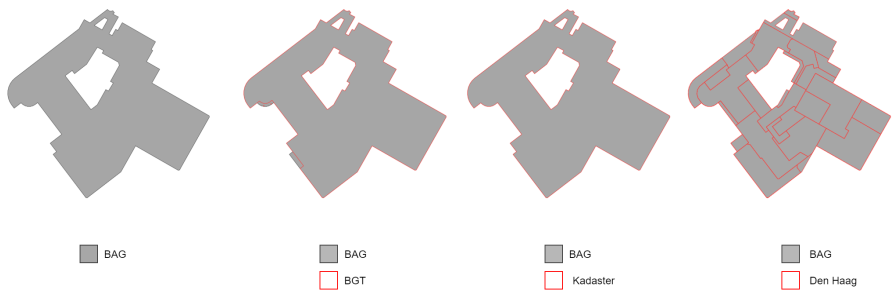


Figure 5.10: Den Haag building 2 footprints

Figure 5.11: Rotterdam building 1 footprints

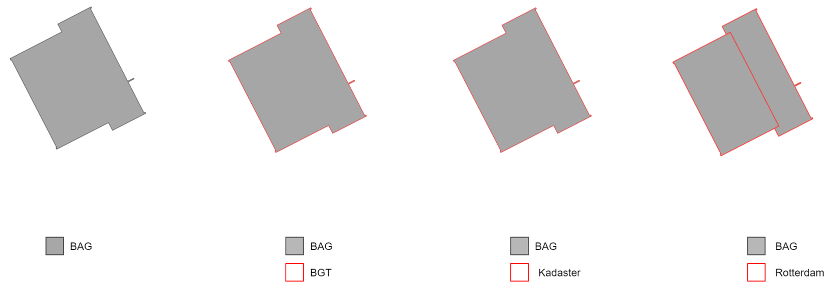


Figure 5.12: Rotterdam building 2 footprints

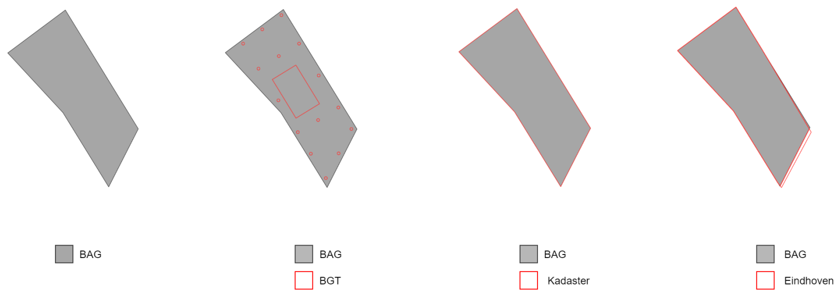


Figure 5.13: Eindhoven building 1 footprints

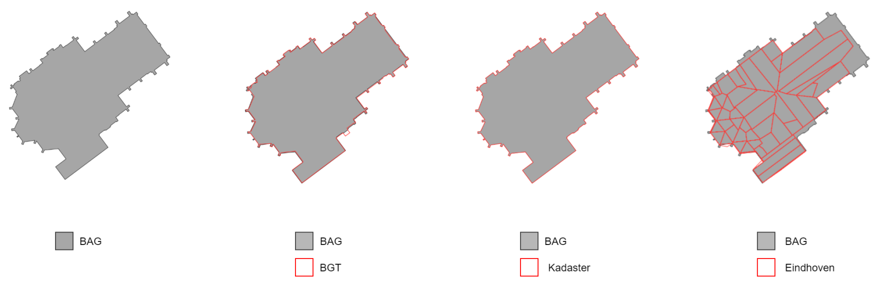
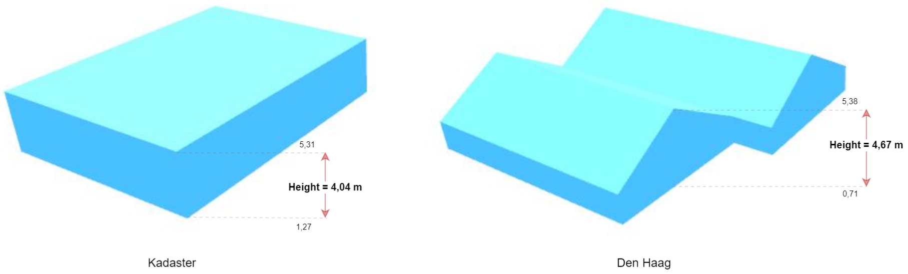


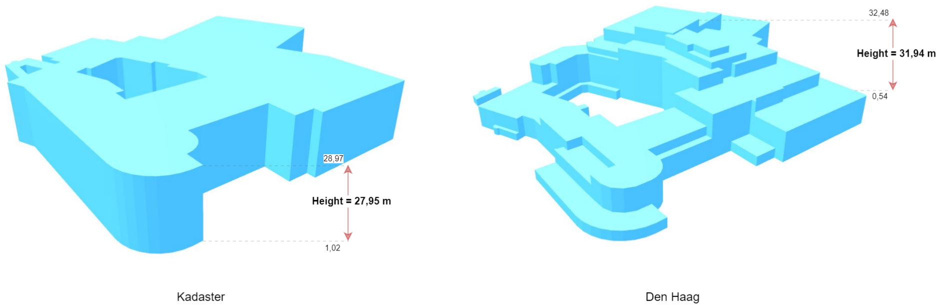
Figure 5.14: Eindhoven building 2 footprints

5.4.2 3D height comparison

In this section the 3D buildings from Kadaster are compared to the buildings of the compliant municipalities. The same buildings as in Figure 5.8 are analysed, showing the terrain Z value, the maximum building Z value and the measured building height. Figure 4.8 shows the 3D models of building 1 and 2 in Den Haag. The terrain height from Kadaster is about 0.50 meter higher than the municipalities models. Figures 5.16 and 5.17 show the results of respectively Rotterdam and Eindhoven. Small differences in the buildings heights can be noticed. These differences are caused by different levels of detail and different construction techniques. Kadaster, for example, calculates the 95-percentile of all AHN-points that fall within one building polygon and takes this as the buildings height. While on the other hand, the municipality of Rotterdam calculates the median height value of these points. In all cases the building footprints are flat, meaning each building has 1 terrain height. Both Kadaster as well as the municipality of Rotterdam, take the height value of the lowest corner point of the building as the buildings terrain height. Thus, in these cases it can be expected that the surrounding terrain is higher than the building itself. For the municipalities of Eindhoven and Den Haag it is not know which height is chosen for the terrain height.

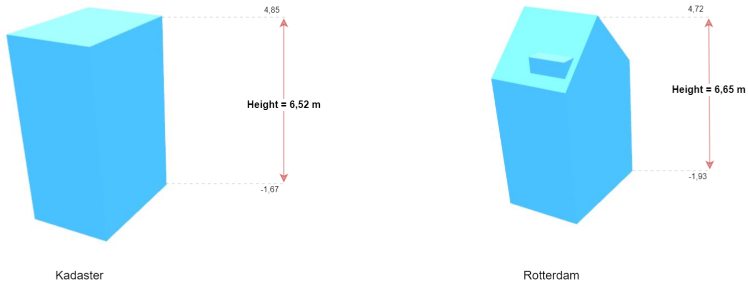


(a)

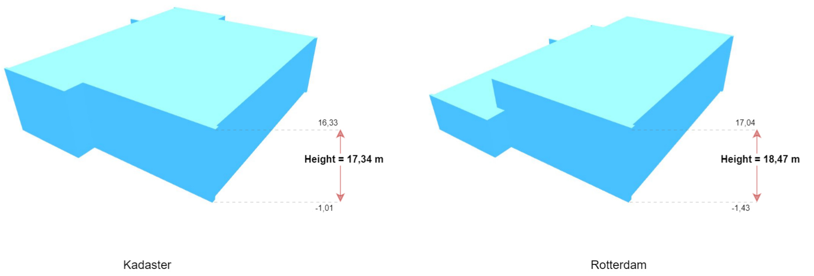


(b)

Figure 5.15: Height comparison: (a) Den Haag building 1 (b) Den Haag building 2

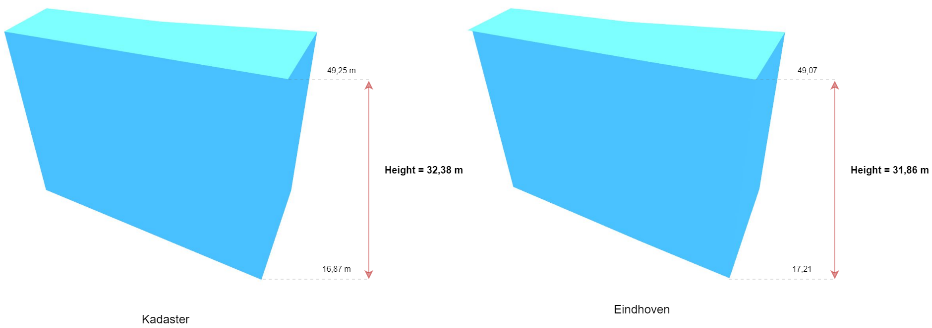


(a)

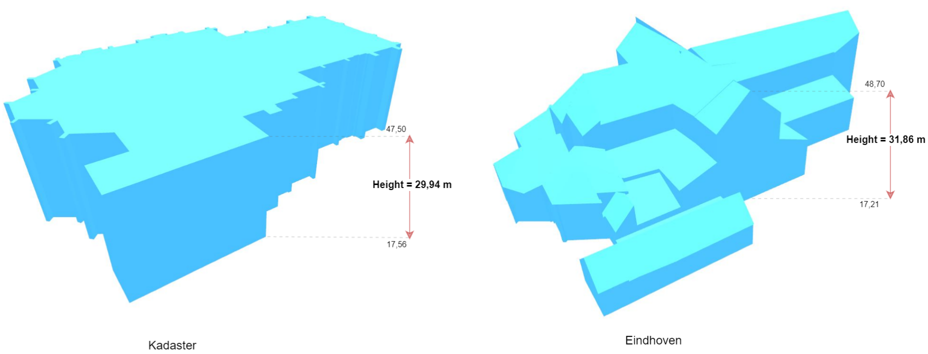


(b)

Figure 5.16: Height comparison: (a) Rotterdam building 1 (b) Rotterdam building 2



(a)

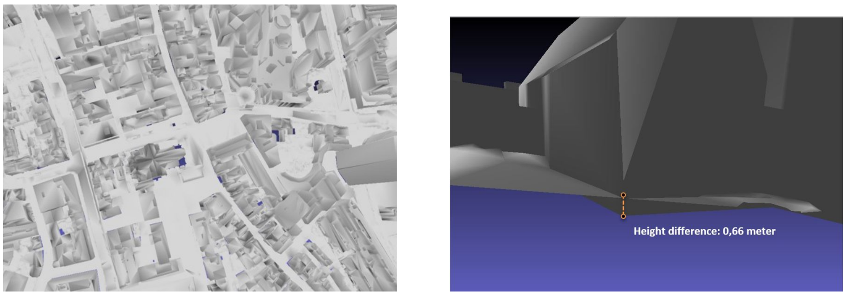


(b)

Figure 5.17: Height comparison: (a) Eindhoven building 1 (b) Eindhoven building 2

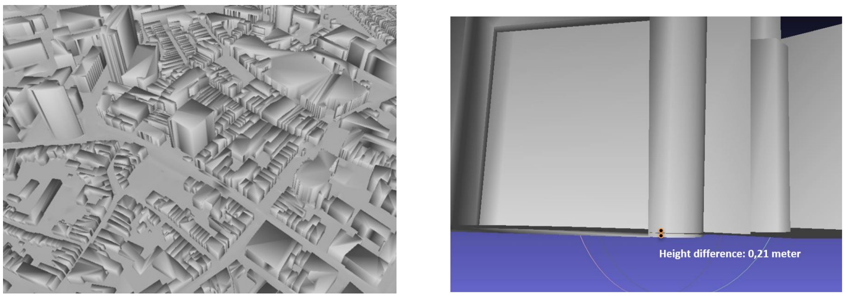
5.4.3 Connectivity building and terrain

This section focuses on the integrated files, analysing the connection between buildings and terrain. The municipalities of Eindhoven, Rotterdam and Den Haag have provided datasets of 3D buildings. These building are merged with the terrain models of the associating location provided by Kadaster. Since Eindhoven also provided a dataset containing the terrain, this dataset is also merged with the buildings provided by the Kadaster. Figure 5.18 shows the first merged file from Eindhoven (buildings from municipality, terrain from Kadaster). Since some of the LandUse features are missing (as reported in Section 4.2) and not all building polygons perfectly match the BAG footprints, holes can be expected in the final merged model. Figure 5.18a visualises the top view of the model, showing some holes (blue parts). Figure 5.18b shows a more detailed view of the model, including the height difference between the building and the terrain. Figure 5.19 shows the merged model with buildings from Kadaster and the terrain from the municipality. There are no holes in this terrain model and the difference in height is about 0.20 meter.



(a) (b)

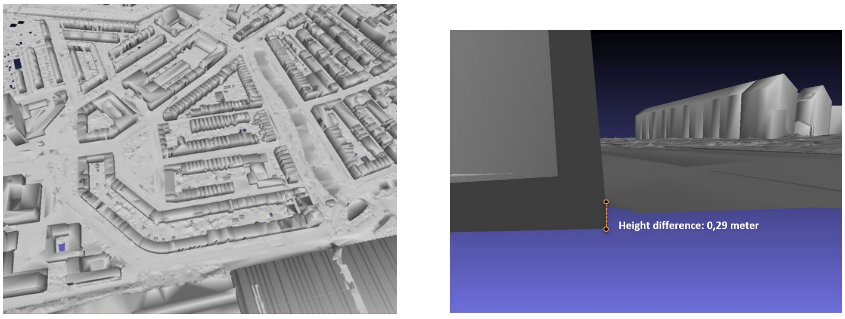
Figure 5.18: Eindhoven (a) Top view (b) Detailed view



(a) (b)

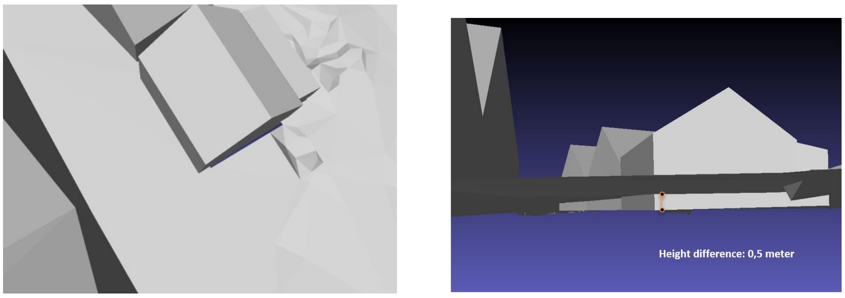
Figure 5.19: Eindhoven 2(a) Top view (b) Detailed view

Figure 5.20 shows the results of the merged file of Rotterdam. Since the footprints of the buildings did match the BAG, it is expected to not find any holes. The top views shows some holes, though they are caused by some missing buildings. This could be because of the different creation dates of the files (in which the building didn't exist yet). Figure 5.21 shows the result of Den Haag. Some small holes can be found in the model, also caused by the building footprints not matching the BAG. The height difference between the buildings and terrain is slightly higher (0.50 m) than for the other locations.



(a) (b)

Figure 5.20: Rotterdam (a) Top view (b) Detailed view



(a) (b)

Figure 5.21: Den Haag (a) Top view (b) Detailed view

5.4.4 Analysis terrain heights

This section will discuss the results of the terrain height analysis. Both Kadaster and the Municipality have provided a CityGML file of the terrain of a similar area. The generation of both models is done with different source data, as stated in Figure 5.2. Thus height differences between both models should be expected. An equally spaced grid of points 2x2 meter (174390 points in total) has been draped on both terrain models, in order to retrieve the Z values of the terrain at the location of the points. After this the difference of the Z values has been calculated, the result is shown in the chart of Figure 5.22. About 87% of the points have a height difference between 0 and 1 meter. A negligible amount of points have a height difference bigger than 5 meter. Yet these values are so big (up to 20 meter), that a visual analysis is needed. A heatmap of the result is created and shown in Figure 5.24. Five locations with the biggest differences are selected for further inspection. Figure 5.26 shows the Google Earth images of all five locations. On these images different situations are shown, pf which each is challenging in the automatic generation of 3D models. The images display a building on water (1), a tunnel (2), railway on a slope (3), a train station (4) and a railway crossing water (5).

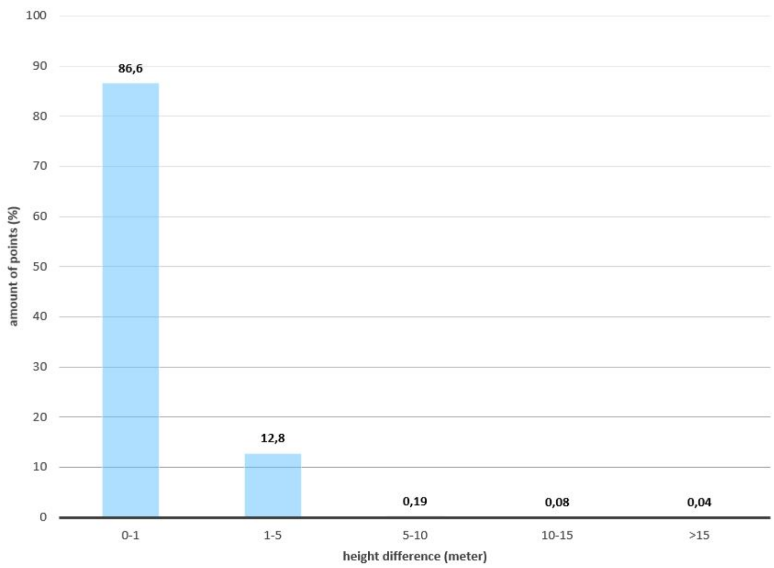


Figure 5.22: Chart terrain absolute height differences Kadaster and Eindhoven

As shown in Figure 5.22, the biggest amount of point has a Z difference between 0 and 1 meter. Figure 5.23 shows the same chart, but in steps of 20 cm. It is noticeable that almost half of the points have a Z difference smaller than 20cm. The calculated mean of the height differences is 0.4989 m and the corresponding standard deviation 0.8665 m.

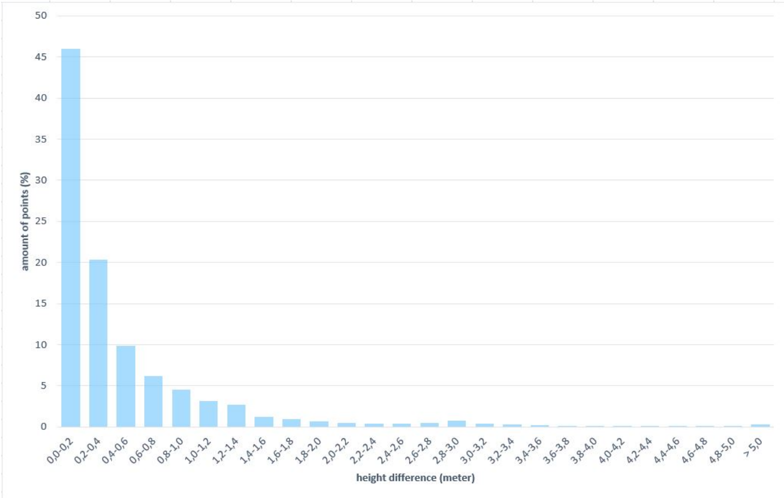


Figure 5.23: Chart 2 terrain absolute height differences Kadaster and Eindhoven

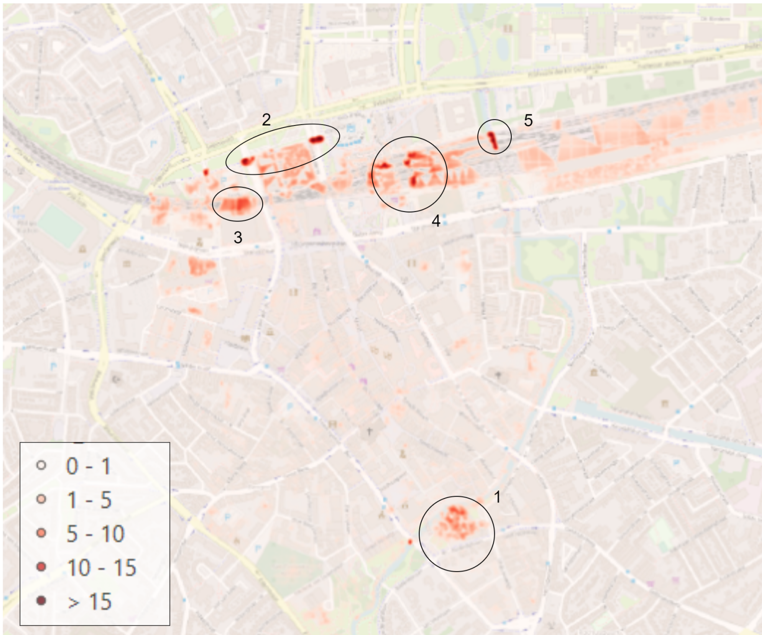


Figure 5.24: Heatmap terrain absolute height differences Kadaster and Eindhoven (m)

Figure 5.25 shows the same height differences of the terrain from Kadaster compared Eindhoven, this time including the relationship between the two terrain models. The blue points have negative values, meaning the Kadaster terrain height is below the terrain height of Eindhoven. The red points have positive values, where the terrain of Kadaster is higher than Eindhoven.

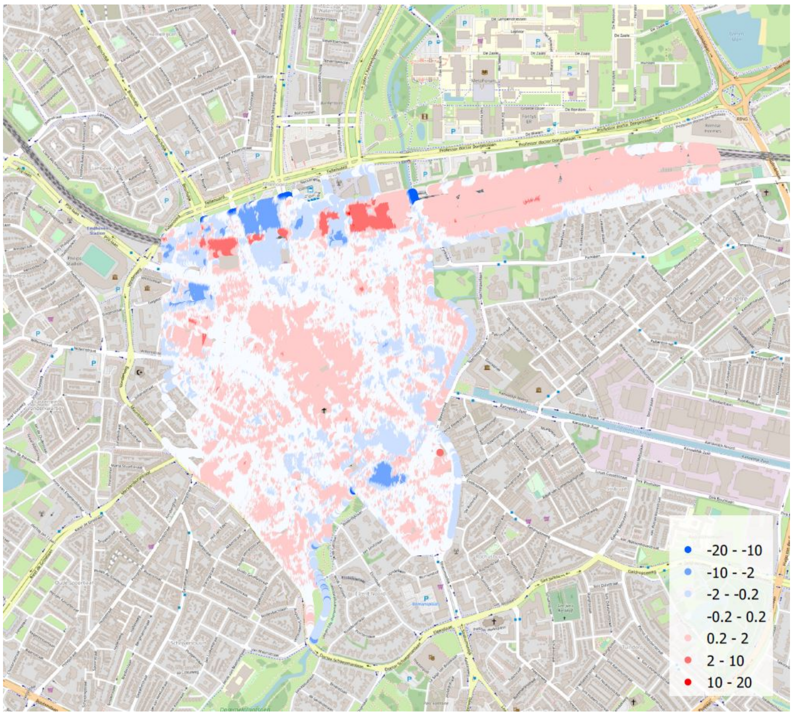


Figure 5.25: Map terrain height differences Kadaster and Eindhoven (m)

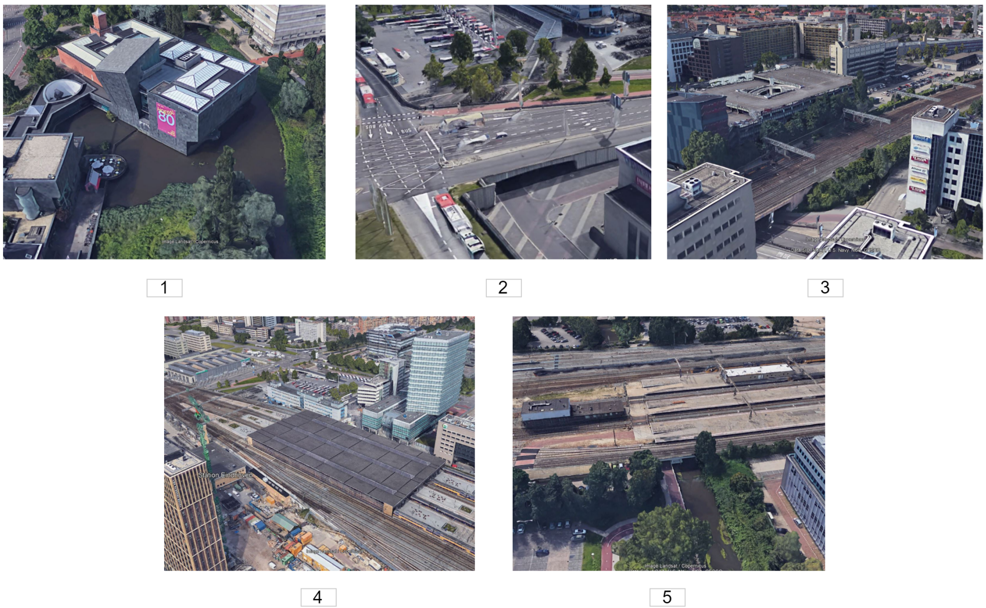


Figure 5.26: Google Earth view of five area's with the biggest differences

For each of the five locations, the median Z-value is calculated, as shown in Figure 5.27. This comparison makes it able to depict the terrain that is the closest to the terrain in the real world. For case 1 for example, the terrain is water and thus the Z-value should be on water level. The height value for this location according to AHN (from `https://www.ahn.nl/ahn-viewer`), is approximately 14 m. The median height of the Kadaster data is the closest to this value, while the value of Eindhoven seems to be way to high. In case 2 a tunnel is shown, from the median values can be concluded that the Kadasters' terrain level is measure in the tunnel and Eindhoven on top of the tunnel. The same conclusion applies to case 5. In case 3 the Z-median of Kadaster seems too high for this situation. The object above the railway might have influenced the modelling process, resulting in a higher surface terrain. In case 4 the Z-median of Kadasters' terrain model also seems too high, which might be causes by the stations building heights.

	Kadaster	Eindhoven
1	15,1	19,7
2	5,5	17,4
3	19,6	15,6
4	24,7	17,2
5	6,4	19,1

Figure 5.27: Median Z-values on the five locations (NAP-height in meter)

5.5 PROPOSAL NATIONAL 3D DEVELOPMENTS

Based on the results from the surveys, interviews and data comparison and integration, two situations have been proposed for further developments towards a national 3D basemap. Option 1 (Figure 5.28) is based on the current state of the BGT in The Netherlands, and adds a 3D basemap of the large-scale topography as an additional open data set. This data will be generated and actualised by the Kadaster. This option is also based on the fact that the development of 3D city models comes with many challenges, thus it should be more accessible for source holders to initiate an approach towards 3D.

This research has been done in collaboration with six stakeholders, of which five are source holders and are organisations of some of the biggest cities. However, there are over 400 source holders in total, of whom not all already have the resources, support and knowledge to develop 3D city models. In conclusion; an integrated 3D base map with different 3D city models should be feasible, as long as the primarily focus is on the accessibility and functionality towards a 3D approach within the organisations. Results have shown that the 3D data of the stakeholders, based on the current state, do not fit perfectly, both semantically as well as geometrically. For example, many differences were found in height values, attributes and footprints of buildings. For this reason, the source holders in proposal option 1 have an additive role and have the option to supply their 3D data to the Kadaster, who will further facilitate the 3D base map. No mandatory restrictions about the data specifications are given. Thus the source holder is free to choose a preferred approach toward 3D, that fits the perspective of the organisation. However, guidelines and resources can be provided to them, in order to support the process and stimulate the creation of 3D city models.

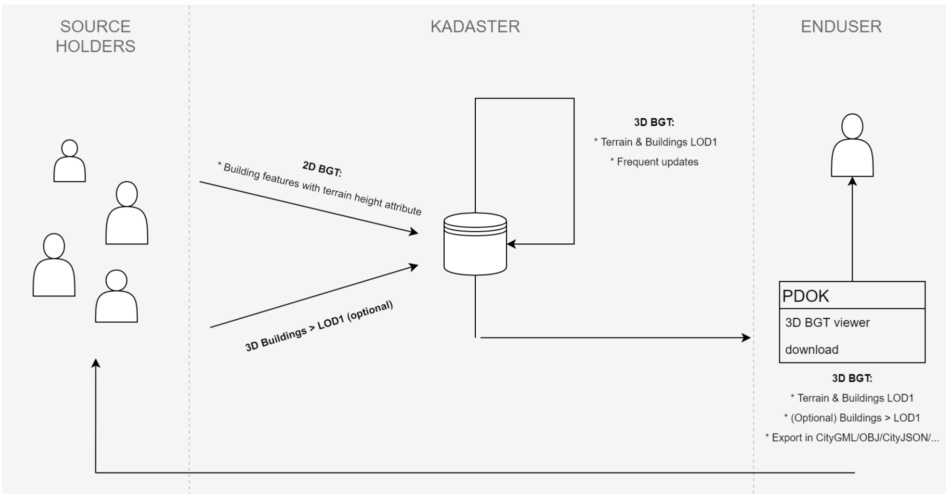


Figure 5.28: Proposed organisational schema towards an integrated 3D basemap - Option 1

The seconds option is based on the aim to create a new 3D basis registration based on large-scale topography. In this second proposal, Kadaster generates a country wide covering 3D base map once, and from that moment on the source holders will have to generate and manage the 3D data for their own regions. Just as in the current situation of the BGT, the source holders parse the mutations and the Kadaster facilitates the data through PDOK. This option can also be seen as the follow-up phase of option 1. The proposed option 2 aims towards the facilitation of a country wide covering 3D base map, in which the data is uniform, complete and has a high accuracy. In order to achieve this, a new (or improved) 3D information model will have to be developed. This information model contains specifications about the terrain heights of buildings, which will be added as a mandatory attribute of each building feature. Also restrictions will have to be made in order to achieve accurate integration of data, without gaps or 'floating' objects in the model. In conclusion; the focus of option 2 is shifted to the data quality and usability of the data. The source holders' additive role changes into an supplying role, since they will be responsible for the collection and reconstruction of the 3D BGT. An comparison between both proposals is shown in Figure 5.30.

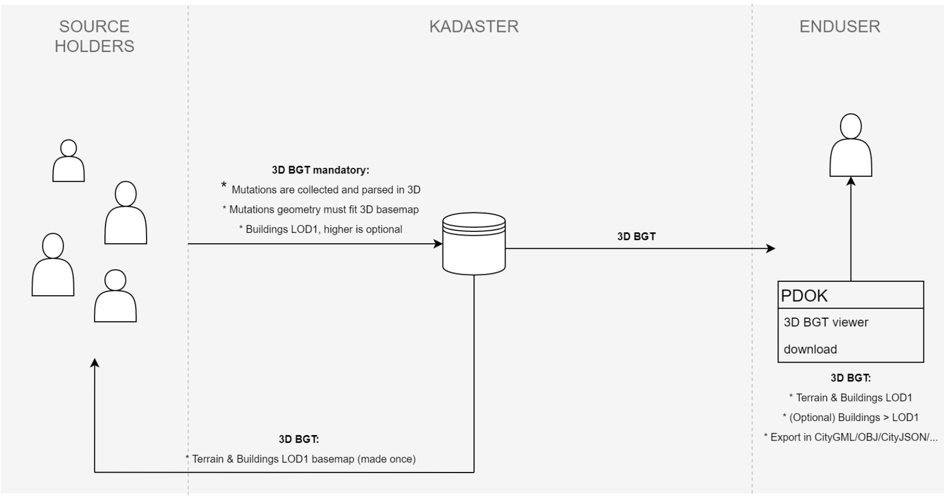


Figure 5.29: Proposed organisational schema towards an integrated 3D basemap - Option 2

	Option 1	Option 2
Goal	• Movement towards 3D is accessible for source holders • Bottom up approach • To provide a national 3D base map and stimulate the creation of other 3D models by source holders • Short term solution	• To provide a geometrically correct, consistent and uniform model • Increase amount of possible applications, by increasing the quality • Top down approach • Long term solution
Role source holders	**Additive role** -> Optionally generate and provide 3D city models > LOD1	**Supplying role** -> Mandatory collection and supply of 3D BGT features
Role Kadaster	• Generate, manage & facilitate the BGT in 3D (as addition to the existing BGT) • Collect additional 3D models by source holders.	• Collect data from source holders, manage & facilitate the 3D BGT (as a new/improved basis registration)
Further requirements	• No restrictions for the additional 3D city models are given • Guidelines / expertise from external (/top) organisations is required	• A new 3D information model based on IMGeo/BGT (or an addition) is required, with at least: - **Terrain Height** will be added as obligatory attribute for buildings - 3D objects representing building must follow **BAG** contours • Improve national height elevation data, containing a higher point density

Figure 5.30: Comparison specifications of option 1 & 2

6 CONCLUSION, DISCUSSION & FUTURE WORK

6.1 CONCLUSION

A wide variety of 3D geo-information needs have emerged in multiple domains and for many different applications. Mapping agencies and organisations in countries all over the world are aiming more and more towards the management of 3D topographic data. This has led to the growth of 3D city models, each with their own specifications, generation process and management. The 3D city models differ from each other concerning their contents, level of detail, quality, completeness and actuality. Thus the interoperability of the 3D city models faces many barriers and remains a challenging task. For this thesis, a case study is done on 3D large-scale topography in The Netherlands. The Dutch national mapping agency Kadaster has been working on the generation of a country wide covering 3D base map. However, also multiple source holders of the Dutch basic registrations BGT and BAG have taken steps towards 3D. The question now arises if an integrated approach towards topographical 3D data is possible and desirable. In the end, an answer will be formulated on the main research question: *"How can a variety of 3D city models be integrated in a country wide covering 3D basemap based on large-scale topography?"*. The answer includes both technical as well as organisational factors.

In order to formulate an answer to the main research question and the sub questions, a methodology consisting of three components has been proposed. The first component contains a literature study, to examine the state of art of 3D city models, their use cases and applications and value. The second component contains the interaction with several stakeholders. These stakeholders are all organisations that are or have been developing 3D (city) models in The Netherlands. The six stakeholders include: Kadaster, the Province of Noord-Brabant, the Municipality of Rotterdam, the Municipality of Den Haag, the Municipality of Eindhoven and the Municipality of Amsterdam. The needs and requirements within the stakeholders organisation have been examined by means of surveys and interviews. The third component contains the technical part, in which the data of the same stakeholders is being compared, integrated and analysed. This component aims to show the barriers and challenges that you come across when the different 3D model are integrated. These challenges have a great influence on the outcome of this research and the proposed answer to the main research question.

To answer the questions from the first subtopic, the state of art of large-scale topography and the developments towards 3D in The Netherlands have been examined. The Netherlands has implemented 10 different basic registrations, which are mandatory since 2016. Two of them are the BGT, containing the (2D) large-scale topography and the BAG, containing data about the buildings and addresses. Different organisations fulfil certain roles and tasks for each basic registration. For example, the stakeholders in this research (except for Kadaster) are the source holders of the BGT data. They are obligated to collect and manage the features that lie within their assigned regions. On the other hand, Kadaster fulfils the role as provider and facilitates the data through PDOK. Different initiatives in Europe have been set up, in order to examine 3D city models, their standards and use cases. Two examples of these initiatives are The Action and the 3D pilot, of which the latter resulted in the establishment of a national 3D standard CityGML ADE in The Netherlands.

The second subtopic is about 3D city modelling. How are 3D city models constructed? What are the 3D standards and information models? And what are the differences between the 3D models of the different stakeholders? There are many different ways to generate 3D city models. Most of these methods involve data sources containing the features footprints and data sources containing height values in order to extrude the footprints to these heights. The two methods used to extract 3D heights, are often divided in photogrammetry based and laser based technologies. Photogrammetry based technologies are mostly preferred for the reconstruction of 3D geometries, as it could provide high accuracy, especially when techniques as DIM are used. In The Netherlands, an open data source with height elevation data already exists. This is the AHN data, which is retrieved by laser altimetry and covers the full country. An example of a tool that is able to reconstruct such 3D city models, is 3dfier, a software tool developed by the 3D Geoinformation group, Kadaster, AMS and STW. 3D city models can be formatted in different ways. This thesis discusses and focuses on CityGML, the national standard of OGC and CityJSON, a more recently developed standard based on JSON. The different 3D models of the stakeholders have been compared to each other, in terms of: contents, source data, format specifications, attributes, geometry and level of detail. Based on the specifications of the test data of the stakeholders, a workflow for the integration of the data has been developed. In this workflow, tools as *cjio*, *citygml4j* and *FME* are used for the manipulation, conversion and integration of the data. Comparison analysis on the geometries of the buildings, have shown that not all the building footprints precisely match the BAG footprint, which, however, was the source data for the reconstruction. Overall, the maximum building heights of the buildings of Kadaster and the other stakeholders, are almost equal. The small differences in the building heights are caused by different levels of detail and different construction techniques. Kadaster, for example, calculates the 95-percentile of all AHN-points that fall within one building polygon and takes this as the buildings height. While on the other hand, the municipality of Rotterdam calculates the median height value of these points. Results have also shown that the terrain height of the buildings differ, with height differences up to 60 cm. These differences are cause by the use of different source data for the heights by the stakeholders. Some use the AHN2, some the AHN3 and other own data or a combination. This height difference causes the buildings in the integrated 3D city models to 'float' in the terrains surface, leading to a distorted visualisation compared to the buildings in the real world. Comparing the 3D models semantically, a big difference in the amount of attributes can be seen. While some of these attribute relate to each other and the original IMGeo attributes, the attributes are all renamed. Thus conversions are needed in order to create a semantically uniform model. Also the terrain model of the municipality of Eindhoven and the terrain model from Kadaster have been compared to each other. An analysis is done on the difference between the Z-values and shows five different complex situations where the terrain modelling could be improved in the future.

Many studies have been researching the use of 3D geo-information, the applications and their data requirements. The different domains in which 3D city models play a role, are amongst others: urban and rural planners, environmental agencies, telecommunications and utility companies, consultants, surveyors, architects and engineers. The study of Biljecki et al. [2015] categorises two groups of applications: non-visualisation based and visualisation based use cases. Visualisation is stated to be an indispensable element in the development of 3D city models. A study on 3D city models in Finland, presented by Julin et al. [2018], defines three main domains for the use of 3D city models: 3D SDI, BIM and 3D game engine based applications. The use cases that have been mentioned by the stakeholders during the interviews include: spatial planning, simulations (water flooding, shadow analysis), participation of citizens in projects and analysis (noise, air quality).
The last subtopic concerns the stakeholders. What are their needs and requirements for the integration of 3D city models into a county wide base map? What would be their role during this process? During meetings with the stakeholders, it was noticeable that there is a lot of variation concerning the knowledge and backgrounds of the persons involved. Furthermore, most stakeholders prefer a supply-orientated approach toward 3D geo-information, since there is a lot of variation within the data purposes and needs. The stakeholders also prefer a bottom up approach towards 3D, instead of a top down approach. There is a lot of variation between the wishes and the reconstruction processes of the different organisations. Though more guidelines and support could be facilitated from higher authorities. In the current state of the organisations, a lack of knowledge of GIS is and a lack of support for 3D are mentioned.

In the beginning the main research question was stated as following: *"How can a variety of 3D city models be integrated in a country wide covering 3D basemap based on large-scale topography?"*. This study has proven that different 3D city models can be integrated in a country wide covering model, which can be converted to various formats (CityGML, CityJSON and OBJ). A workflow is developed that integrates the test data of 5 Dutch source holders with the data from Kadaster. A few challenges during the conversion and integration of data had to be overcome. These challenges were either caused by errors in the code of the test data or by bugs and errors in the software tools. In the end, two proposals were given for further developments towards a national 3D basemap based on large-scale topographical data. These proposals were based on the results of the literature study, the interviews with stakeholders and the data comparison and integration. In option 1, a national 3D basemap, developed and managed by Kadaster, is proposed. In option 2, a new basis registration, the *3D BGT*, is proposed. In this situation Kadaster will provide a 3D basemap once and the source holders will collect and parse the mutations in 3D.

6.2 DISCUSSION

During this research, a method is developed in order to integrate different 3D city models based on large-scale topography. The research has provided new insights to the differences between 3D city models in The Netherlands. However, the data from the stakeholders is currently still being developed, meaning the method is applicable to the current state of art and does not take further developments into account.

Secondly, the results of the surveys, interviews and meetings provided new insights into the needs and requirements of the stakeholders. A similar case study hasn't been done before in The Netherlands. Though, the outcome is limited, as the methodology included the interaction with 5 source holders, while there are over 400 source holders in The Netherlands. These 5 source holders also include 4 of the biggest municipalities. The needs and developments of smaller municipalities are thus not a part of this research. Also other source holder organisations, such as the Water Boards and ProRail, haven't taken part in this research.

During the last phase of the research, second meetings had been set up with some of the stakeholders. The research results were demonstrated by means of a presentation and feedback was provided by the participants. During these meetings it became clear that most of the participants were unaware of the data and developments of the other stakeholders, so this research provided insights in the developments of other organisations. They were also unaware of some of the technical results, such as the fact that the building footprints of some of the 3D data did not match the original footprints from the BAG.

During the meetings, feedback was also given on the organisational proposals for further national 3D developments. The participants state that it still remains unclear what the final requirements and needs of the 3D data are. Thus further research of the use cases and applications of national 3D basemaps are required, for both proposals.

The opinions about the proposal option 2 for further national 3D developments were divided. It had been mentioned that the collection and managing of the 2D BGT is already a difficult task in the current situation of the basis registrations. The collection of 3D data would be an even more challenging and more expensive task. From their perspective, they do not yet desire a 3D BGT, as a new basis registration, in the nearby future. However, on the other hand it has also been mentioned that a national 3D BGT might be introduced sooner than expected. In this situation, a higher authority should guide the developments and finance the collection of more accurate and actual height elevation data.

6.3 FUTURE WORK

Due to limited time and resources, other interesting research questions, analysis and tests have been left out during this research. Recommendations for future work are summarised below.

- In this research, a literature study is done on the possible use cases and applications of 3D data based on large-scale topography. Further research could be done on the use cases and applications of this 3D data in The Netherlands, in which the specifications and needs of the 3D data for these applications are examined in detail. The results of such research could be used to expand the organisational proposals with an technical aspect.

- During the analysis of the data results, the test data of the stakeholders is compared to each other. This analysis could be extended with a research on the data quality and a comparison to the true values. Such research could provide answers to the question: 'which data is the most accurate and closest to the real world?'.

- Except for the terrain height analysis in Eindhoven, which is done partly automatic, the data comparison analysis in this research has been done almost fully manually (and visually by eye). To improve this analysis, further research could examine ways to automatically compare 3D city models on terrain and building heights and matching footprints. A higher amount of comparisons and statistics will improve the reliability of the research results. Automatic comparison techniques could possibly also speed up the analysis phase.

- If the BGT data in the future will be collected and parsed by the source holders in 3D, as proposed in option 2, further research could be done on the integration of 3D data based on mutations. What would be the best technique to collect or generate this 3D data?

- An important aspect of data, that is left out of this research, is the management of the data. One of the software tools that is used by a large group of source holders, is *dg DIAGLOG BGT*, a tool that is developed by the international engineering company Sweco. The application includes the collection, construction and management of BGT data in The Netherlands. Further research could be done on the management swift from 2D to 3D data., which is already being investigated by Sweco and other organisations.

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COLOPHON

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