# Verification of the suitability of CityGML city models as a data basis for simulations at urban district level using extracted information from façade images

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**Abstract.** The semantic and geometric information gathered in city models (often in CityGML format) are usually the data basis for larger scaled urban planning considerations and simulations by being largely available nationwide. Thus, the results of the simulation strongly depend on the geometric accuracy of the city models. The paper investigates this geometric accuracy and describes the concept and implementation of the application ABBA which verifies its accuracy. Furthermore, ABBA enables to manually process façade images for geometric and semantic building information such as windows, wall openings and doors and map the information. The reconstructed building information will be compared with CityGML models and the building plans to evaluate the geometric accuracy by comparing it with the real dimensions of the buildings and extended by the new building parts. The results show that ABBA is suitable as an alternative and for verification purposes, with a comparable accuracy to the CityGML models.

## 1. Introduction

For urban planning considerations and simulations, various semantic and geometric building information is a prerequisite in order to achieve a certain degree of planning reliability by recording the actual condition. However, there are only a few freely available and area-wide data sources on which to base this information. The digital capture of information about the current built environment is often done only for individual buildings, using measurements or emerging techniques such as the *scan-to-BIM*-method. In general, digital building models from BIM, which are increasingly being produced in the design of new buildings, provide a rich source of information for individual buildings, but they are usually not public and therefore not a comprehensive source of information. The cost and complexity of these methods make them unsuitable for area-wide coverage. Many simulations in the district context, such as energy or $CO_2$ simulations, are based on city models in CityGML format, which are increasingly available in the public domain in Germany in LOD 2 like the published models by the *Hessische Verwaltung für Bodenmanagement und Geoinformation*[1]. Current city models serve primarily as a geometric data basis, while the semantic information required for the application still has to be introduced via additional data sources. As a result, simulations are highly dependent on the accuracy of the city models. According to information from German state authorities shown in Kunz (2021), the height accuracy is in most cases within one meter. However, in some cases rough deviations are possible. In Kunz (2021) some possible reasons for this deviation are presented, such as complex roof situations or nearby vegetation. However, there are no representative statistical surveys that specify the geometric inaccuracy more precisely. This is partly because validation of these values is only possible by manual comparison with building plans, which are often difficult to obtain, or by independent measurement. This paper addresses two of the above issues. On the one hand, it presents two different approaches to provide a first access to the use of BIM models as a data source at the district level. The developed approaches

[1] https://gds.hessen.de/INTERSHOP/web/WFS/HLBG-Geodaten-Site/de_DE/-/EUR/ViewDownloadcenter-Start

use different data sources to extract the contained building information of an existing building and to build a BIM model from it, by partially automatically generating geometric and semantic building information with minimal, easily, and publicly available input values. While one approach uses façade images combined with map information to extract building information, the other approach uses CityGML city models as input. The façade image approach also extends the information provided by the CityGML models (LOD2) by adding building part information such as doors and windows to the model to achieve LOD3 standard. The aim is to demonstrate a current state of the art in semi-automated BIM model generation, and the potential for further development. On the other hand, these approaches provide the opportunity to evaluate the geometric building information of the same buildings, but reconstructed from separate data sources, generated by the different approaches. The geometric deviations between the calculated building values and the CityGML values are evaluated to validate the accuracy by comparing them with the real dimensions of the buildings extracted from floor plans.

## 2. Official 3D building models in Germany

Official 3D building models are increasingly being made available by public administrations in Germany, and more and more use cases are being presented, as in InGeoForum: 3D-Stadtmodelle (2023) .The model description in Germany is developed and defined by the AdV in the form of a product standard (AdV, 2021) and a data format description. These documents are the basis for the modeling of buildings by the surveying authorities of the federal states. AdV (2021b) defines the two LOD levels LOD1-DE for LOD1 and LOD2-DE for LOD2, which are also freely available. Further LOD levels such as LOD3 and LOD4, as presented in Gröger et al. (2012), do not play a role, because the state of the art does not allow the generation of such city models for large quantities. On the one hand, accuracy depends on the LOD of the city model. In general, the higher the level of detail (LOD), the higher the accuracy (Gröger *et al.*, 2012). However, even within the same LOD, quality attributes give an indication of geometric accuracy. Therefore, the results of simulations based on city models can be influenced by the quality attributes of the city models. The quality of city models in CityGML format depends on the methods used to create them and, on the inaccuracies, associated with each method. When creating city models in CityGML format, the required data is obtained through the combined use of different methods and sources. To provide this and other information, the city model is tagged with metadata. In addition to information about the *creation date*, *roof type*, *floor plan update* and *geometry type* of the 2D reference, data sources are also defined (Kunz, 2021). The methods are declared separately for the data sources for *roof height*, *floor height* and *floor plan* for each building. Depending on the availability of the data sources, the information from the different methods is merged in an automated process. The attribute *data source location* defines the method and source, which is used to capture the 2D geometry. This geometry describes a 2D representation of the building and its building parts. In AdV (2021b) six different characteristics are defined whereby four of these six are a direct derivation of data from real estate cadastre. This cadastre keeps up-to-date and comprehensive records of all plots of land and buildings as well as their exact position. Continuous updating through statutory requirements for land and building surveys ensures that the cadastre is kept up to date and the procedures used in this process guarantee a high level of positional accuracy. The data source of the *real estate cadastre* distinguishes the data according to the method or source used to obtain the data. It is divided into *unspecified data*, *calculated data*, *digitized data*, and *data derived from topographic survey*. *Data from topographic survey* can also be used directly as data source for location. Alternatively, the location can be determined photogrammetrically. As shown in Schwarz (2021), about 97% of the data bases for the location of buildings in LOD1 in Germany originate directly from the real estate cadastre. The accuracy of the locations is defined differently in different sources. In Gröger *et al.* (2012) the position is proposed to be 2 m or better. In official documents in Germany like AdV (2021b) the location accuracy it is often equated with the accuracy of used cadaster. In case of real estate cadaster, Alkis (2022) defines different levels of accuracy depending on the *collection method* and estimates the accuracy in the range of "centimeters to decimeters".

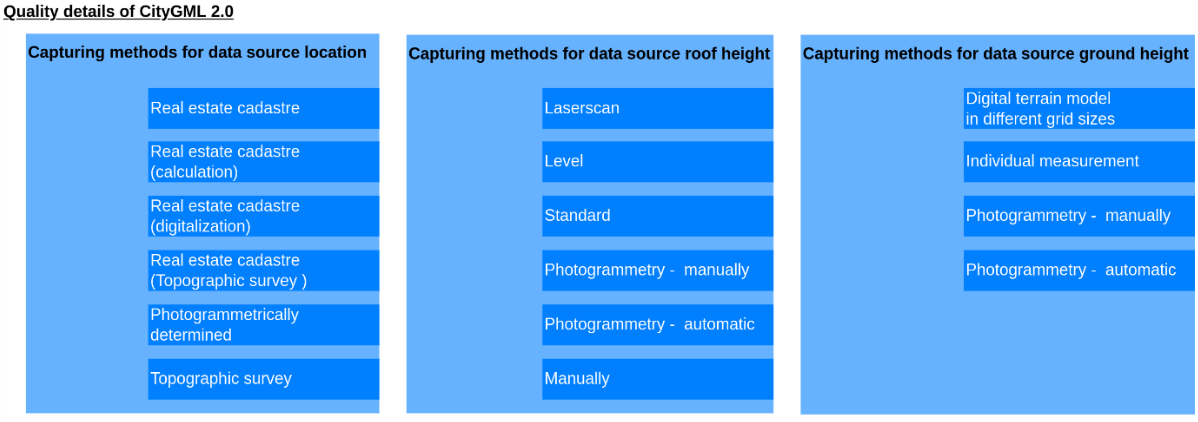


Figure 1: Capturing methods of CityGML.

The *roof height* data source defines the method used to estimate the height of a building. One method is *laser scanning* while the most used sub method is ALS (Airborne Laser Scanning) which is described in Ressl, Mandlburger and Pfeifer (2009). The point clouds resulting from laser scanning are the starting point for the creation of digital surface models and digital terrain models as well as for 3D city models. Alternatively, automated and manual photogrammetry can be used to estimate the roof height by stereoscopic image analysis methods. The product of automated photogrammetry is the image-based digital surface model, which is described in more detail in ATKIS-DOP (2022). The *manual method* describes the measurement procedure, which is carried out by a surveyor on site. The characteristics *level* and *standard* are estimation methods, which are used if no measuring point is available. One opportunity in the standard method is to set the height information depending on the floor space. If an information about the number of levels is given, the level method can be used to predict the building height with the help of an estimated level height. In Schwarz (2021) it is shown that about 70% of the databases for the height information of buildings in LOD1 in Germany are based on the *laser scanning* method. Another 20 percent are based on *automated photogrammetry*. In general, official documents in Germany such as Kunz (2021) estimate height accuracy in the range of one meter, although exceptions are possible. Gröger *et al.* (2012) estimate the height accuracy within two meters. The data source *ground height* describes the method and source, which is used to determine the ground height of a building. Digital terrain models can be used with different grid widths from one meter to 1,000 meters. Alternative sources are *on site measurements* or *manual or automated photogrammetric surveys*. Schwarz (2021) identifies digital terrain models with grid widths of one meter to ten meters as the main data source for ground level building information in LOD1. AdV (2021a) estimates the ground level accuracy of a digital terrain model with a grid width of one meter in the range of five centimeters. These three data sources are combined to derive the actual building dimensions. While the *location* data source provides the 2D information about the position of the building, the *ground elevation* data source extends the ground information into 3D information by adding the elevation information. The *roof height* data source provides the height information of the roof and therefore the building.

## 3. Different methods of generating BIM-information and -models

In the context of this work, different approaches are presented that allow a partially automated transfer of information about individual buildings from façade images and city models into building information and BIM models, thus creating an extended database at the building level.

### 3.1 Façade image-based building information

In order to validate and enrich the information contained in CityGML LOD2 buildings, the application "ABBA" (German: "Automatisierte -Bild Bemaßungs- Anwendung", "automated image measuring app") has been developed. It combines different types of data sources and uses computer vision algorithms to (semi-automatically) collect building information that produces CityGML LOD3 level information such as external dimensions and window/door geometry. The application uses a combination of semantic and geometric map data and images of building façades. The following paragraphs describe the different data sources that can be used by ABBA and the structure and functionality of the application. To ensure that the application is widely usable and can be further automated, it is important that the input data is as publicly available and universally applicable as possible. Therefore, there is always a trade-off between accuracy and generality, which is also discussed in Chapter 5. Basically, the data sources can be divided into semantic and geometric information provided by (publicly available) maps and various data sources of façade images of buildings. For the map information, there are several publicly available 2D (and sometimes 3D) alternatives such as Open Street Map, Wikimedia maps, ALKIS, CityGML, etc. From these sources, the geometric polyline of the building outlines (or models in LOD1 or 2) as well as semantic data such as address information, building type, number of floors, etc. can be obtained. An overview of the different attributes available for OpenStreetMap (OSM) buildings can be found on their website[2]. The outlines of OSM buildings are generated from aerial photographs, but in some cases also from on-site measurements (OpenStreetMap Wiki, 2023). To ensure that different map types can be used in ABBA, it is implemented as a Python plugin for QGIS, an open-source geographic information system. For the collection of building data and the validation of CityGML models, the building information from OSM is used, as it contains map and building information from all over the world. The building geometry information and addresses from OSM were filtered using the *Overpass Turbo* website[3] and imported as a merged layer into QGIS. ABBA requires a visualisation of each façade area. In the following context, a façade is defined as one side of the building, including the wall, windows, doors and wall openings. If the building has a rectangular floor plan (and therefore consists of four façades), ABBA needs four images (one for each façade) or two images including two façades from the corner of the building. The image can be taken by the user with a smartphone, digital camera, drone (which allows good angles to the façade), action cameras (which have a high FOV and allow façade images in narrow areas) or publicly available images such as Google Street View or Mapillary, or aerial images can be included. Depending on the dimensions of the building and the required accuracy, an adequate image quality is needed. For the results in Chapter 5, a smartphone (Google Pixel 5, 4032 x 2268 px) and a digital camera (NIKON D7200, 6000 x 4000 px) were used without compromising in accuracy. After importing the OSM map into QGIS, the user can select the buildings they wish to edit and open the ABBA plugin. The building outlines are imported into an ABBA project and the semantic information of the buildings can be viewed and edited. When a building is selected, its outline polyline of the building footprint is also displayed and can be edited. The *Façade Editor* allows the corresponding image of the façade

[2] https://wiki.openstreetmap.org/wiki/Key:building.

[3] https://overpass-turbo.eu/.

to be linked to the line of the building's outline polyline. Once the image has been selected, the following image processing pipeline is applied to calculate the height of the façade and generate additional information about the building parts:

1. Undistorting the image: Although not as visible with smartphones and digital cameras as with fisheye lenses such as action cameras, lines in an image are (more or less) curved by the camera lens. By calibrating the cameras, the intrinsic and extrinsic properties of the camera (distortion coefficients and camera matrix including focal length and optical centres) can be calculated by evaluating images of a calibration image. These camera properties can be used to correct the tangential and radial distortion effect in new images taken by the camera. This reduces the distortion (fisheye) effect caused by the camera lens to a very small value, which can be calculated as the so-called re-projection error. The process of calibration and undistortion was inspired by the OpenCV documentation (OpenCV, 2023). For the test study, it was done with the described cameras by taking 15 pictures with each camera and calculating the camera values.

2. Rectification: Assuming that a façade (including the containing components) is more or less a flat rectangle, the following procedure describes how the images of the façade can be transformed in such a way that length and area measurements can be read directly from the image. If the four corner points of the façade are known, the image can be "rectified" using linear transformations as shown in Zhang and He (2007) or in Permutohedra (2016)**.** The selection of the four corner points could be determined by computer vision algorithms such as edge detection or object recognition of façades, or in the context of ABBA, selected by drawing a polyline around the corners of the façade. To determine the transformation parameters, nine degrees of freedom must be calculated and collected in a Homography matrix: three for the 3D positioning of the camera in relation to the façade rectangle, three for the rotation of the camera, two for the dimensions of the finished rectangle (façade height and width) and one for the focal length of the camera. As the two dimensions of the finished rectangle (façade height and width) are still unknown, the width is read from the OSM length of the building side and the height is estimated using the Zhang and He (2007) algorithm. The focal length of the camera has already been calculated (step 1) and the translation and rotation of the camera can be calculated by selecting the four corners of the façade using Zhang and He (2007). After the image is rectified, the outer areas of the image that do not contain façades are cropped.

Figure 2: Undistorted image with marked corners of the façade.

Figure 3: Same image that got rectified and building parts are marked.

3. Read out building parts: After step 2, the image consists of the plain façade, which is true to scale and has no perspective, as shown in  in contrast to . This means that the aspect ratio of width to height is also in proportion to the dimensions of the façade. With the known width of the façade and the width of the image in pixels, a conversion factor can be calculated between real world metres and pixels in the image. This allows any pixel distance in the image to be

converted into real world distances, assuming the principle of a pinhole camera as in OpenCV (2023). This can be used to calculate the real height of the façade and by drawing a bounding box around windows, doors and wall openings, their dimensions and position in the façade can be calculated. Building parts can be manually selected by drawing a rectangle around the building parts which can be extended by an automated image detection algorithm as proposed in the current research project Thiele ( to be published).

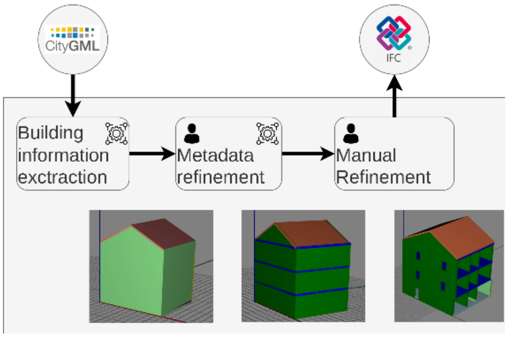


Figure 4: CityGML based approach.

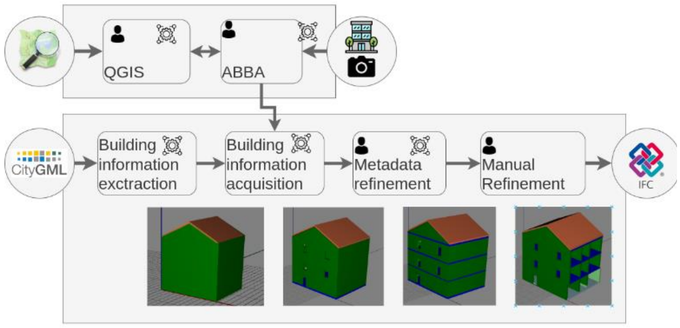


Figure 5: Workflow of combined approach.

### 3.2 CityGML based building information model

City models in CityGML format are increasingly available to the public in Germany. However, the data format is limited in its ability to represent more detailed information about the building, as is possible in BIM models. Therefore, in this approach, also shown in **Error! Reference source not found.**, individual buildings from the CityGML model are transferred into a BIM format to be able to use and extend the building information as a data basis in a BIM model. The whole process takes place in successive steps within a specially developed tool. In the first step, the building information is extracted from the CityGML and a BIM model is automatically created. On the one hand, the building information is taken over and on the other hand, the individual components, which are characterized as specific components in the CityGML format via surfaces, are built up into a geometric and semantic BIM model. In order to further enrich the BIM model, another semi-automatic reconstruction based on metadata is performed. User specifications for the number of storeys, height and basement level allow the BIM model to be automatically extended to include intermediate ceilings and external walls below ground level and their assignment to storeys. In a final step, the BIM model is transferred to BIM authoring software. In this software, based on the previously automatically generated BIM model, further information can be added that cannot be automatically captured in the current process. This approach allows the automated reproduction of the cubature of a building in a BIM model. It is possible to add building information through metadata in an automated way. Finally, the BIM model can be completed to the desired depth, but this requires manual work and, in most cases, a great deal of effort.

### 3.3 Combined approach using façade image and CityGML based Tool

Another approach is the combined use of ABBA and the CityGML based tool, shown in **Error! Reference source not found.**. Firstly, it is possible to take the full building information from ABBA, stored in a JSON schema, into the CityGML based tool without using any information from CityGML. The JSON schema is based on the IFC hierarchy and includes all the geometric and semantic information collected for each building part. The building information captured in ABBA, including components such as external walls, roofs, floors, windows, and doors is read into the CityGML based tool. For this purpose, the façade image-based approach is used as usual. The resulting building information, stored in a proprietary data format, is integrated into the existing pipeline. The addition of an extra step after the building information extraction allows the integration of building information extracted from façade images and OSM. Using the geometric information and the semantic context, a BIM model is built that organizes the semantic information and visualizes the geometric information. Further steps for detailing the BIM model, as already presented in Chapter 3.2, can be connected. Another option is the combined use of the façade image and the CityGML data source. Due to the state of the art in capturing building information for CityGML in LOD2, it is not possible to obtain information about windows and doors in façades. For this reason, the CityGML approach requires this information to be added during manual refinement in a non-automated way. For further automation, information already obtained in the CityGML model regarding the ground, external walls and roofs is maintained and additional information such as door and window information can be taken from ABBA to obtain a more detailed building information model.

## 4. Test study

In the first part of this paper, different approaches are presented that deal with the digital recovery of geometric building information of individual buildings from different data sources and the transfer to BIM and thus in a semantic context. The presented approaches use different applications to semi-automatically generate geometric and semantic building information with minimal, easily, and publicly available input values. In the next step, the results of two different approaches (one based on façade images, and one based on the CityGML city model) will be evaluated to compare the geometric accuracy of these approaches. As the combined approach only merges the two data sources using the other two approaches, it is not considered in this step. This evaluation should also allow a first conclusion to be drawn about the geometric accuracy of the two approaches. To be able to refer to the exact reality, geometric building information based on plan data is also part of the evaluation. For this evaluation, the building cubature information generated by the different approaches is available and evaluated. The dimensions (height above ground of the buildings and the ground dimensions of the buildings) of the building models and plans were compared with the building plans. These represent the *as-planned* version of the building. To verify these dimensions, several lengths of the test buildings were measured with a laser distance meter. These measurements differed from the floor plan dimensions by a maximum of 3 cm. As introduced in Chapter 2, CityGML models can be based on different data sources for roof height, ground height and location. For this reason, the CityGML model of Darmstadt will first be evaluated with respect to these data sources to identify the main methods of derivation. In a second step, the buildings used in the evaluation are analysed in the same way. The CityGML model of Darmstadt contains 64,068 buildings. In terms of the data sources for ground height and location, this analysis provides a clear result. The ground height information of all buildings comes from *Digital Terrain Model 1*, which means that the grid width of the model used is one meter. The location information for all buildings is also based on a single origin, the cadastre. This means that the more detailed origin of the cadastral data, such as digitisation or calculation, is not specified. This is in line with the results for Hesse in Schwarz (2021), where it is found that in Hesse only *Digital Terrain Model 1* is used for *ground elevation* information and the cadastre is the only data source used for location information in LOD1. Different data sources are used for *roof height* information. *Laser scanning* is used as a data source for about 95% of the buildings. The *standard method* is used for 4% of the buildings. A minority uses photogrammetry and the manual method as sources of information. The proportions for *laser scan* and *standard method* are similar to the results for LOD1 in Schwarz (2021). In contrast, *photogrammetry* and *manual methods* are also used for a small number of buildings for LOD2 data. The test study includes ten buildings with 40 façades. According to the previous results, the *ground level height* information for all buildings is derived from the *Digital Terrain Model 1* and the location information for all buildings is based on the cadastre. On the other hand, the source of the *roof height* data is approximately equal between the *laser scan* and the *standard method*. The purpose of the test study is to answer the following questions: Is it possible to achieve the same geometric accuracy with the help of façade image-based approach like in the CityGML approach regarding height and ground dimension information? Further is investigated: How far deviates the same geometric information form CityGML from the real building by comparison with plan data and is the deviation of one meter always fulfilled?

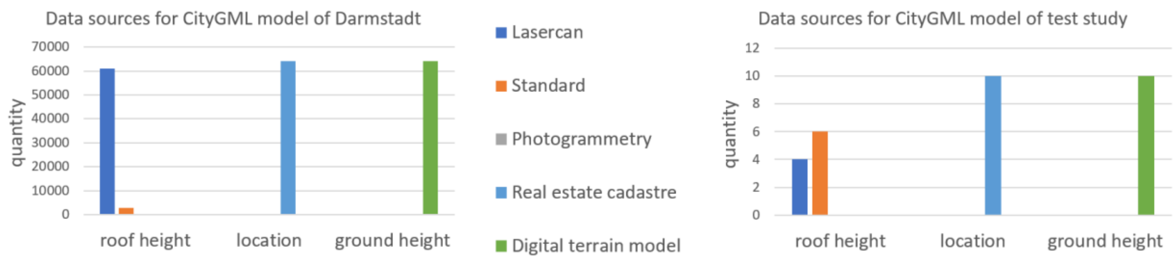


Figure 6: Data sources of regarded CityGML models.

## 5. Results and discussion of (in)accuracies

The results of the test study are shown in Table 1. The results are differentiated for the façade image-based approach using ABBA and the CityGML based approach. In addition, the results of CityGML are further separated for the two different data sources for height information. The results are shown as absolute values and as a percentage of the *as-planned* values from the plan. The percentage values are shown because ABBA is linearly dependent on the base length. Because the data origin of the length value of the two methods of CityGML are the same, the results for the length are listed separately in the *combined* line. In order to get a better overview of the deviation, the results for the average deviation as well as the standard deviation and variance are shown, separated by the values for the height of the buildings and their dimensions of the plan, as shown in Table 1. While the mean absolute deviation and scattering of height information in ABBA is lower than the results of the CityGML models, the mean absolute deviation and scattering for base lengths of ABBA are much higher in comparison to CityGML results. Based on this, the current façade image-based process only estimates height information a bit more precisely than CityGML but not the ground information, which is why CityGML based geometric building information are classified as geometrically more accurate

When working with the presented data sources, models and methods, different types of inaccuracies and error propagation can occur. As the test study is not representative for all data sources, these errors are listed and discussed for future studies, divided into inaccuracies of the city models caused by building features and inaccuracies of the ABBA image processing pipeline. The ABBA image processing pipeline has several inaccuracies which are described in the following. The undistortion of the images depends on the accuracy of the camera calibration, which is discussed in Chapter 3.2. The rectification depends on the accuracy of the marking of the corners of the façade, the rectangularity of the real façade and the computer vision algorithms. The way the image is captured affects the angle of the camera in relation to the façade (very sharp angles make it less accurate). The image quality and the camera also affect the results through parameters such as FOV and image resolution. Apart from this minor source of error, the test study showed that the floor plan measurements from OSM are not as accurate as the CityGML values (shown in Table 1). By using ALKIS, which is used in CityGML, as an input to ABBA, more accurate measurements could be made by ABBA itself, as all recorded values depend on the base length of the façade taken from OSM.

Table 1: Deviation between floor plan to respective method: results of the test study.

| **Method** | **Height (abs. [m])** | **Height (rel. [%])** | **Height [Dev/Var]** | **Length (abs. [m])** | **Length (rel. [%])** | **Length [Dev/Var]** |
|---|---|---|---|---|---|---|
| ABBA | 0.47 | 4.56 | 0.54/0.29 | 1.64 | 8.74 | 1.33/1.76 |
| CityGML (laser) | 0.34 | 4.93 | 1.68/2.81 | - | - | - |
| CityGML (standard) | 0.84 | 4.95 | 1.35/1.81 | - | - | - |
| CityGML (combined) | 0.64 | 4.94 | 1.12/1.25 | 0.22 | 1.28 | 0.27/0.08 |

The CityGML has higher values for height information, especially scatter, compared to low deviations and scatter for base lengths. On its own, the mean absolute deviation is below the set limit of one meter, but in combination with the standard deviation it is statistically achievable. In detail, only one building out of ten is outside the set limit with a deviation of 3.74 meters, which is the main reason for the high level of dispersion. On the one hand, the reasons for this high deviation in one case can be sought in complex geometric buildings, but all the buildings used have simple geometric structures and flat roofs. On the other hand, the source of height information used may be a reason. Whilst all the buildings surveyed with the laser can are within the set limit, the outlier detected was surveyed using the standard method, which does not allow any precise conclusions to be drawn about the origin of the height information. While observing and working with the CityGML models, it was noticed that building parts such as attics, roof installations, atriums and large roof overhangs are not represented in the city models and cause inaccuracies because their dimensions have to be compressed into the CityGML building models. The CityGML models and the ABBA approach do not take a basement into account. While CityGML models have information about the ground level as a line on the building wall, ABBA can only process the information shown on the images. However, this can be used to document the actual condition of each visible side of the façade and, if required, to calculate an average height or to process the different heights as additional information. In general, the statement about height information is covered by the results of this work and, together with the high accuracy of the ground dimensions, city models provide a solid basis for simulation in urban district simulations. Prior to a simulation, the quality details of the considered urban district should be analysed in order to get a first understanding of the methods used and the associated inaccuracies. Also, geometric features of individual buildings that are not captured by current methods, such as atriums and large roof overhangs, can affect simulation results.

## 6. Conclusions and Further Research

The paper presented research on the accuracy and origins of CityGML models and described a process to verify the measurements of buildings and to extend these city models from LOD2 to LOD3 by adding information about building parts such as doors and windows. The process and the application ABBA were verified by a test study and the results and the (in)accuracy and its dependencies were discussed. The next steps would be to further automate the data collection process. Images could be automatically analyzed from street images such as Google Maps or Mapillary based on their geo-information. The image processing pipeline could be further automated by using computer vision algorithms to detect the corners of the façade and the parts of the building. As an alternative to the introduced image processing pipeline, photogrammetry and multiple images could be used to generate 3D information about the building façades and the roof type including its geometry. To verify the accuracy of the selected information, with a larger database of available building plans, the geometry could be automatically read from the plans, automating the verification process.

## 7. Acknowledgements

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