Quality of 3D Building Models Derived from Airborne Laser Scanner

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by

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Disclaimer

Dedicated to my love, Tanis

Abstract

Nowadays, Three Dimensional (3D) models are used widely in human life in several fields such as architecture, civil engineering, entertainment, medicine and city models. City models are suitable for various applications such as urban planning, vehicle navigations, 3D cadastre and facility managements. 3D building models are one of the main components of city models. Quality of 3D building models is important to judge about their usability in different applications. Different modellers/researchers had used various methods for assessing the quality of their models/reconstruction methods. For assessing quality of 3D models lack of using unique standards and comprehensive quality aspects that can describes quality of models in more aspects still exists.

In this thesis, after reviewing various used quality issues, different quality aspects were introduced and described for assessing the quality of 3D building models. In this case, each 3D model was divided into three main parts: Body, roof and dormers. For each part, some related quality aspects were proposed and discussed. Roof similarity and geometry of roofs were presented as quality aspects related to roof parts. Dormer's reconstruction rate and geometry check of dormers were presented as quality aspects related to dormer's part and for body part, positional accuracy, footprint correctness and height accuracy were introduced. The main idea was preparing quality report for each set of models by means of assessing the introduced quality aspects. With this quality report, users due to their requirements are able to judge about the usability of reconstruction method, used input dataset and set of 3D models. Moreover, making decision about the correctness of 3D model (or set of models) would be possible by having comparison between prepared quality report and user's requirements.

On the other hand, by evaluating quality of two different sets of 3D models that were reconstructed from ALS (as their input dataset), pros and cons of each of the used reconstruction method were discussed. In this case, 3D building models were reconstructed in both semi-automatic and automatic method by selecting some sample buildings were selected with a defined building selection strategy. Quality aspects of each of the selected building models in both sets were assessed. By assessing all introduced quality aspects for each model individually, quality reports for each set of automatic models and semi-automatic models were prepared. With helps of this quality reports and discussion on quality of each aspect, it was concluded that, shape of footprints, shape of roofs, overhangs in models are crucial components that influence the quality of 3D models. The effects of human interpretations were also observed.

Moreover, results of assessed quality aspects of automatic models were compared with quality measures that can automatically be generated from automatic reconstruction method. These comparisons concluded that quality measures that automatically generated in automatic reconstruction method are useful for assessing roof similarity and height accuracy of 3D models. The results of these automatic generated quality measures were correct in roof similarity and accurate in height accuracy of 3D models.

Keywords: Airborne Laser Scanner (ALS), Quality assessment, 3D building model, Quality report, Semi-automatic approach.

Acknowledgements

"The circle where our coming and going lie.
Has no known beginning nor end.
No body can tell truth in this matter.
Where do we come from and where do we go?"

Omar Khayyam, Persian poet, 1131AD

Although we don't really know what will happen exactly in the end of our life, I think we must have goal and do our best in each steps of our life and also enjoy Irreversible moments. I would like to show my gratitude to special people, who have played an important role in my life, especially in this period.

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Pooya Jalali
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1. Introduction

1.1. Motivation and problem statement

Nowadays, especially due to being more user friendly and ease of use, Three-Dimensional (3D) presentations of urban features are a better technique to view located-based information (Zhang et al. 2005) for natural resources such as vegetations, and man-made objects such as buildings and roads. Many applications of 3D city models such as car navigation and service browsing, tourism and marketing, architecture and town planning, city climate and environmental research try to have a better visualization of 3D space in recent years (Zhang et al. 2005).

For reconstruction of 3D buildings different input datasets are introduced by many authors for manually or automatically modeling such as Airborne Images (Remondino and El-Hakim 2006), Airborne Laser Scanner (ALS) (Habib and Rens 2009), and vector 2D-GIS (Zhang et al. 2005). Also in some related works the combination of different datasets for reconstruction of 3D models are used. With different types of 3D modeling methods and different types and resolutions and quality of input datasets and also the required application, the 3D model is reconstructed in different Level Of Details (LOD) (Oude Elberink and Vosselman 2010a) and with different quality. The quality of used input datasets and the following processing steps have direct effects on the quality of reconstructed 3D models (Habib and Rens 2009).

Airborne Laser Scanner (ALS) is one of the utilizable input datasets that can be used for extraction of 3D building models and becomes more popular because it provides a faster collection of 3D data over a large area (Tse 2008). One of the uses of ALS is extracting height and shape of the features with point cloud datasets for reconstructing 3D models. In addition of ALS, modelers also use 2D-GIS in vector format as input dataset for positional information of their 3D model (Oude Elberink 2010; Zhang et al. 2005).

The quality of 3D reconstruction models is important for different usage and applications and also for finding the results in comparison to reality. There are various standards and definitions and different ways for assessing the quality of 3D models. Usually different researchers/modelers choose different methods and sometimes used their own method for checking the quality of their work such as Martin Rutzinger in 2009 who used three different methods (Pixel-Based evaluation and Object-based evaluation by evaluating the mutual overlap) for evaluating 3D reconstructed models (Rutzinger et al. 2009b). Some of them control the quality of the input datasets to estimate the reconstruction 3D model (Habib and Rens 2009), some of them calculate the quality of the method of reconstruction (Baltsavias 2004) and others check the quality and calculate errors of their 3D model with comparison to reference data (Oude Elberink and Vosselman 2007).

Some of these methods are not defined in standards but are defined by researchers/modelers individually. In this case each method that used for checking the quality of 3D models by researchers/modelers are different from others, and there is a problem with comparing quality of different works in 3D modeling because different factors and methods has been chosen and used for quality control of different models. The reason of this problem is using different method of quality controls by researchers/modelers and also lack of using unique standards for 3D reconstruction model quality. This problem affects more in the case of choosing the best method of reconstruction 3D models by comparing the quality of different results of each method. In evaluation of different works, there are problems because the modelers using their own methods for control the quality of their work.

1.2. Research identifications

Due to the problems of using different quality control methods, the main aim of this thesis will focus on collecting different quality methods and standards that are available for reconstruction of 3D model and to develop and propose aspects for assessing quality. For solving this problem, various quality aspects for assessing quality of each 3D model will be introduced in this thesis. By assessing these quality aspects, preparing quality report for each model (or set of models) would be possible. With this quality report, users due to their requirements are able to judge about the usability of reconstruction method, used input dataset and set of 3D models. The following objectives of this thesis have been shown in the following sentences.

1.2.1. Research objectives

- Review available standards and quality control methods relevant to quality of 3D reconstruction models based on Airborne Laser Scanner (ALS) as input data and discuss them.
- Propose quality aspects which cover more perspectives of 3D models for assessing the quality of 3D models.
- Produce two sets of models by using automatic and semi-automatic modeling techniques as a quality criterion and for comparison.
- Compare the result of semi-automatic and automatic modeling with each other and prepare quality report by assessing quality aspects for each set for comparing the quality of 3D models in each method.

1.2.2. Research questions

- What are the relevant standards for quality controls of 3D models?
- Which quality aspects should be assessed for quality control of reconstructed 3D models based on ALS input data?
- What are the crucial components that influence the quality of 3D models?
- What is the influence of semi-automatic and automatic approaches in the quality of 3D reconstruction model?

1.2.3. Innovation

In this research the comparison and discuss between the quality of 3D building models that reconstructed with automatic and semi-automatic method and preparing quality reports for each set of 3D models are such an innovation in quality control by having a deeper insight in the behavior of the quality of 3D building models.

1.3. Structure of the thesis

Chapter one, Introductions: This chapter covers motivation and problem statement, objectives, research questions and innovation aims to achieve during this thesis.

Chapter two, Quality aspects: This chapter reviews the previous work related to this research and introduces various quality aspects that are related to different parts of 3D building models.

Chapter three, Reconstruction methods: This chapter introduces used input datasets and adopted reconstruction methods, the modelling steps for each reconstruction method are discussed, and the results of reconstructed models are shown in each set.

Chapter four, Quality assessments: This chapter presents the discussion on the results of assessing quality aspects for each reconstructed model and for whole set of 3D building models.

Chapter five, Conclusions and recommendations: This chapter provides final conclusions and recommendations for future works.

At the end of this thesis, after list of used **References**, all 22 reconstructed models with semi-automatic method and used ALS has been shown in **Appendix**.

2. Quality aspects

2.1. Introduction

Nowadays, Three Dimensional (3D) models are used widely in human life in several fields such as architecture, civil engineering, entertainment, medicine and city models. City models are suitable for various applications such as urban planning, vehicle navigations, 3D cadastre and facility managements (Kaartinen et al. 2005).

For reconstruction of 3D city models, several input datasets can be used for this procedure such as Airborne Laser Scanner (ALS) (Pfeifer et al. 2007), Terrestrial Laser Scanner (Walter 2007), Airborne Images (Baltsavias 2004) and Terrestrial Images (Remondino and El-Hakim 2006). Each of these datasets has its own characteristics, for example ALS detects roof shapes better (Oude Elberink 2010) or aerial images are good enough for capturing building textures (Remondino and El-Hakim 2006). Nowadays ALS becomes more popular due to collecting 3D data over a massive area (Tse 2008). In this thesis the Airborne Laser Scanner (ALS) is going to be used as input dataset.

Quality checking of input dataset is important for knowing that the input dataset is effective for chosen application or not. That means the usability of input dataset for the specific application must be check by quality controlling before using the data for reconstructing 3D model. In the field of 3D city modelling, geo-datasets must be used and input dataset (such as ALS). The quality parameters for any geo-dataset categorized into the following six criteria (Guptill and Morrison 1995):

1. Positional/height accuracy (the accuracy of 3D coordinates): Means checking geometry of input dataset to reference data. Positional accuracy is the accuracy of coordinate's values and it's often made between absolute (external) and relative (internal) positional accuracy. Relative positional accuracy is comparison of data to same data test and "absolute positional accuracy is the accuracy of test coordinates values relative to matching reference coordinate values on the same coordinate system" (van Oort 2006).
2. Semantic accuracy: Objects and attributes of input dataset must be in correct and valid class.
3. Completeness: Input dataset must be complete in comparison to reference data.
4. Correctness: The values of input dataset must be valid.
5. Temporal conformance: Input dataset must have temporal validity.
6. Logical consistency: Logical rules should be same for all objects.

Each of the above criteria's has its own effect on the 3D model that will be reconstructed. For reconstructing 3D models, different methods have been using such as manual, semi-automatic and automatic (Kaartinen et al. 2005). Each of these methods also has their own effect on the final 3D model. In this case semi-automatic and automatic methods are going to be used as reconstruction method.

On the other hand because of the input dataset and the required application, the 3D reconstruction model will be represented in different Level of Details (LOD) and for city models five different LODs are suggested by CityGML (Walter 2007):

- LOD-0 defined as regional model, 2.5D DTM and 3D landmarks.
- LOD-1 defined as city models and block models without roof structure.
- LOD-2 defined as city models, houses with roof structures and textures and vegetation.
- LOD-3 defined as city models, house structures with details, vegetation and road furniture.
- LOD-4 defined as indoor model and architecture models with details.

The following Figure 1, shows some examples for different LODs (Gröger et al. 2008):

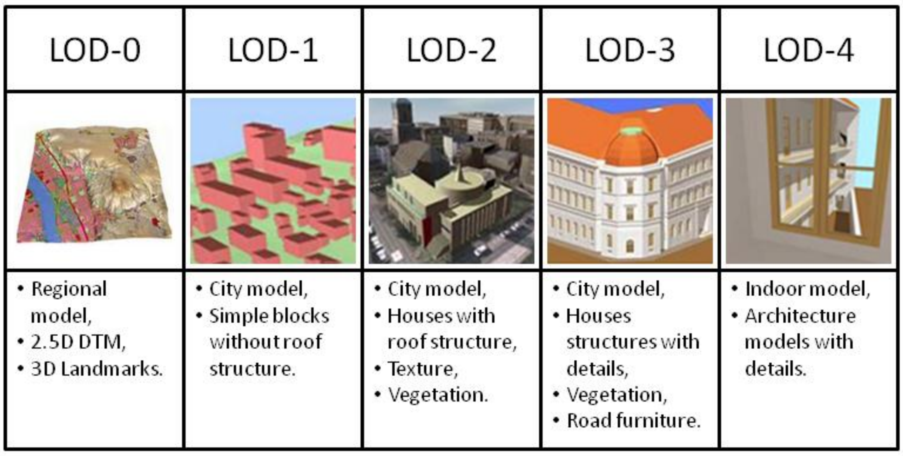


Figure 1: Shows differences between each LOD.

Just LOD-2 will be mentioned and discussed in this paper because the focus of this research is only on reconstruction of 3D building models.

For 3D reconstruction models the evaluation of model is an important step and the quality of model must be controlled (Sargent et al. 2007). Due to the quality control, usability of 3D reconstructed model will be accepted or not for the chosen application.

The quality of 3D reconstructed model is separate from the quality of input dataset but by some error propagations it will be possible to estimate the quality of 3D model from input dataset (Oude Elberink 2010). Figure 2 shows the schematic relations between output quality assessment and input dataset quality assessment and reference data:

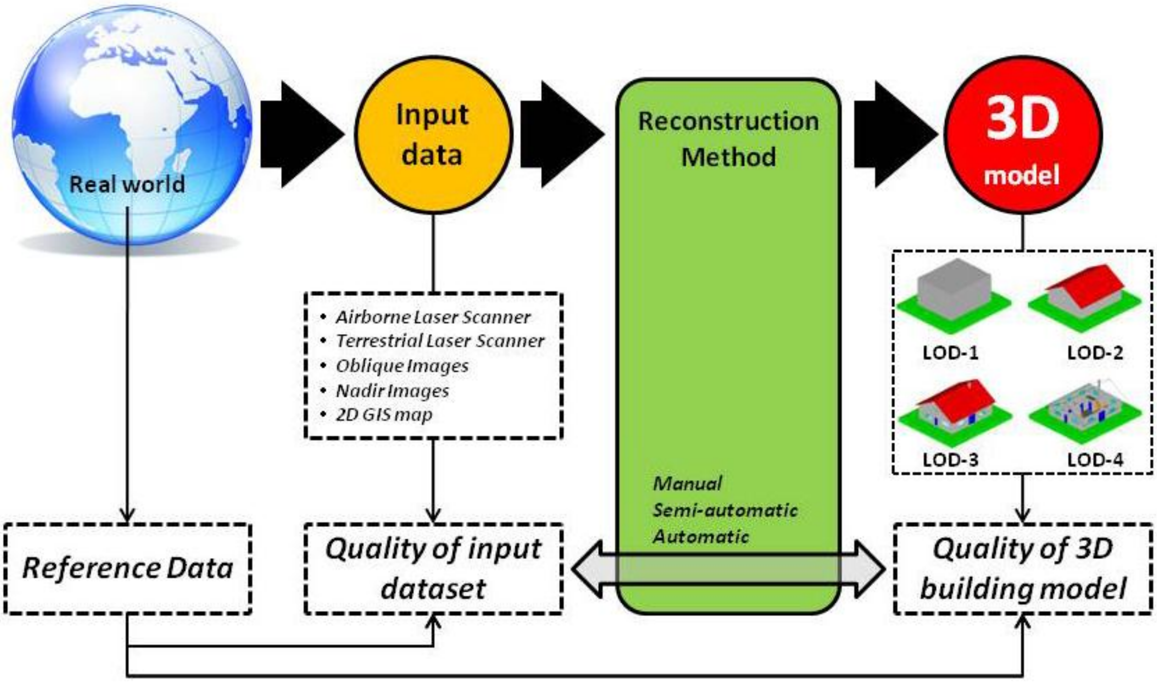


Figure 2: Schematic relation between reference dataset, input dataset, output dataset.

As Figure 2 shows, quality assessment of output (3D model) is separate from the input quality assessment and quality aspects of 3D building models must be checked independently from input dataset. But there is a relation between quality of 3D reconstructed model and quality of input dataset and reconstruction method (Oude Elberink and Vosselman 2010b).

2.2. Related works

In the field of quality assessment of 3D models, some related works had been done. For this purpose, some of the authors define their own quality assessment methods or characteristics for assessing the quality of their 3D models. In the following, used quality aspects by different authors in different projects will be reviewed:

1- (Vosselman and Dijkman 2001)

Vosselman & Dijkiman (2001) reconstructed 3D building models by using Hough transform for extracting planar faces from point clouds that were distributed irregularly and ground plans of buildings with using two different strategies. First strategy tried to detect intersection lines and height jump edges while the second strategy considered that all of detected planar faces should be model some part of the buildings. Comparison of these two modelling strategies was done by checking some quality aspects on their outputs. The main focus was on the number of reconstructed models, number of correct or incorrect models were reconstructed; and how detailed the model were reconstructed (the number of reconstructed details such as dormers and chimneys) and the correctness of reconstructed details (Vosselman and Dijkman 2001).

2- (Rutzinger et al. 2009a)

Rutzinger et al. in 2009 presented an automatic method for detecting and extracting vertical walls as part of 3D building models by using Hough transform. They used mobile laser scanning data (MLS) and airborne laser scanning data (ALS) as input datasets for their procedure. Visibility and completeness of the extracted results were checked for comparing the differences between results of using MLS as input data and using ALS as input data. This comparison was measured by the number of extracted wall segments and wall lengths in meter (Rutzinger et al. 2009a).

3- (Haithcoat et al. 2001)

Haithcoat et al. in 2001 presented a fully automatic approach for extracting building footprints and reconstructing 3D models. Their approach just needs to input few parameters for start reconstruction procedure. For checking quality, they first visually controlled the results of their method. For quantitative accuracy assessment they checked following 7 aspects:

Completeness and correctness were measured by comparing number of extracted buildings with reference data. Completeness represents percentage of reference data being extracted and correctness indicates the percentage of correctly extraction.

For geometrical accuracy, Root Mean Square (RMS) was measured. Due to the lack of height information of their reference data, they just measured horizontal RMS by calculating the distance between corresponding building corners.

Besides, by comparing extracted roof types with reference data the roof classification accuracy were obtained.

And finally for building shape similarity checking, the following indicators were used: overlay error, perimeter difference and area difference. By overlaying extracted buildings with reference data, the above indicators were measured (Haithcoat et al. 2001).

4- (Suveg and Vosselman 2004)

Suveg and Vosselman in 2004 presented a method for reconstructing 3D models, with combining the aerial images and 2D GIS information. Due to the lack of ground truth data, they inspected the final building models visually; for assessing their performance.

They defined reconstruction rate as one of the quality aspects. For this purpose, they composed two metric evaluation functions: $S_{contour}$ and $S_{texture}$. $S_{contour}$ was used for verifying the resulted 3D models and $S_{texture}$ was used for checking the 3D models validation. They classified their reconstructed models into 3 classes by comparing the results of these two metric functions. If both metrics were positive, generated building models were certainly good and be in “green” class. If just $S_{texture}$ was negative, generated building model maybe good and were be in “yellow” class. And when both metrics were negative, wrong model or non reconstructed models were in “red” class. They find out buildings in “yellow” class, are actually correct but because of un-modelled small roof structures such as small dormers, their $S_{texture}$ was negative and they were be in “yellow” class.

For measuring reconstruction accuracy, they calculated and compared the results of Average and RMS of the parameters (length, width, height and gable height) of identical buildings models because of not having ground truth data (Suveg and Vosselman 2004).

5- (Schwalbe 2005)

Schwalbe in 2005 checked quality of the 3D reconstruction method with calculating “success rate” of correctly reconstructed buildings. The author concluded that the success rate of his method for simple regions is close to 100% while for complex buildings is between 40-50% (Schwalbe 2005). There isn’t any information about the method of calculating the “success rate” for practical verification of this modelling method.

6- (Sargent et al. 2007)

This group tried to gather information from customer requirements in the field of 3D data quality. After that by identifying some characteristics, this group tried to define accuracy of these characteristics for different users’ field of work. In the following, characteristics that were defined by this group will be introduced:

A. Geometric fidelity: the represented 3D model must have accurate shape or alignment in comparison to real world. The accuracy of characteristics related to geometric fidelity is variable and depends on user context.
    - Characteristic 1: Inter-building geometric shape.
    - Characteristic 2: Roof geometric shape.
    - Characteristic 3: Complete building geometric shape.
B. Relative positional accuracy:
    - Characteristic 4: Position and dimensions of doors and windows.
C. Absolute positional accuracy: the following characteristics and their quality requirements are relative to Geodetic Datum and Terrestrial Reference System.
    - Characteristic 5: Highest point of structure.
    - Characteristic 6: Maximum height of roof ridge.
    - Characteristic 7: Height of building to base of roof (eave height).
    - Characteristic 8: Ground floor height (Sargent et al. 2007).

7- (Kaartinen et al. 2005)

EuroSDR compared 3D models reconstructed from different input datasets either with semi-automated approach or automated approach in 2005. They analyzed results of this evaluation by calculating Minimum, Maximum, Medium, Inter Quartile Range (IQR) and Mean Square Error (MSE). They mainly used IQR as quality measured of the models. In this case, reference points were used for analyzing the accuracy of location, length and roof inclination of models. Also single points were analyzed for planimetric and height errors (Kaartinen et al. 2005).

8- (Akca et al. 2008)

The least square 3D surface matching evaluation method (LS3D) was introduced by the cooperative work between the chair of photogrammetry and remote sensing ETH Zurich and the research department or Ordnance survey as costumer. Their method tries to respond to customer requirements and be independent from the way of capturing data. Their proposed method addressed the following quality criteria:

- Reference system accuracy, by calculating any differences (rotation, transformation) between two datasets.
- Positional accuracy
- Completeness, visually check to find out which buildings are missed (Akca et al. 2008).

9- (Dorninger and Pfeifer 2008)

Dorninger and Pfeifer in 2008 presented an automatic 3D approach for building reconstruction. They discussed about the result of their method by comparing results of several projects for example they compared visually outlines of their models with areal images as reference data. For evaluating the quality of huge models, they suggested an automatic method that can analyze if buildings completely modelled or not (Dorninger and Pfeifer 2008).

10- (Pfeifer et al. 2007)

They compared extracted building footprints with reference data in 3 comparison methods:

- Low level pixel comparison: Used producer's accuracy (PA) (Completeness) and User's accuracy (UA) (Correctness) for comparing the classification to reference data.
- Comparison on the object level
- One implementation of an object level comparison: Comparison "central point" of objects with reference data by 3 different methods and classified results in four (strong, partial, weak, none) classes (Pfeifer et al. 2007).

11- (Walter 2007)

Walter in 2007 completed the list of quality aspects of spatial data. He listed 8 quality aspects and defined them, but there isn't any information about how to measure these quality aspects: Lineage, Accuracy, Availability, Metadata, Completeness, Correctness, Consistency and up-to-dateness are quality aspects that Walter listed in his paper (Walter 2007).

12- (Oude Elberink 2010)

By some quality analysis, the author was mentioned that quality of input data, situation of capturing dataset, and variation in laser point density; input dataset gaps have relation on the quality of the extracted features. Also by comparison between input dataset and extracted models with calculation of some measurements, users can analyze quality of models (Oude Elberink and Vosselman 2010b).

13- (Crombaghs et al. 2002)

This group by dividing total error budget into 4 components described a new height precision method for laser DEM. In their opinion, 4 components of total error budget are: Error per point, Error per GPS observation, Error per strip and Error per block. For measuring error per point (point noise), they used cross correction for calculating standard deviation for all differences between interpolated height and originally measured height; and used it as laser point noise (Crombaghs et al. 2002).

14- (Schuster and Weidner 2003)

Schuster and Weidner represented new approach for quality evaluation in 2003. Their evaluation consists of an evaluation of the building detection by assessing quality rate and evaluation of the building reconstruction by assessing weighted quality rate (Schuster and Weidner 2003).

15- (Rutzinger et al. 2009c)

After comparing some evaluation techniques for building extraction from ALS, Rutzinger and his colleagues were described several methods for determining completeness, correctness and quality of extracted buildings. They described pixel-based evaluation for raster representation and object-based evaluation for vector representation of the buildings (Rutzinger et al. 2009c).

16- (Cheng and Gong 2008)

In 2008, Cheng and Gong introduced a method for building boundary extraction. They used high resolution imagery and lidar data as input dataset for their method. For evaluating their method, they assess correctness of extracted boundaries by checking distance and angle between extracted boundaries and their corresponding in reference. If the angle difference was less than 3 degrees and the segment distance differences were less than 5 pixels they considered extracted segments correct (Cheng and Gong 2008).

17- (Rutzinger et al. 2010)

For change detection of building footprints in short time intervals, this group used ALS captured in different times. In this case by simple overlay, they compare the results and classify them into five different classes. By checking the results visually with images as reference they classified buildings into unchanged building, new building, demolished building, new building part and demolish building part classes (Rutzinger et al. 2010).

18- (Keqi et al. 2006)

This group checks the results of their automatic method for extraction buildings footprint from airborne lidar data by qualitative and quantitative analysis. In qualitative method, they checked direction of extracted footprints visually from reference. And in quantitative method, they compare and calculate omission and commission errors for extracted footprints (Keqi et al. 2006).

19- (Wenbo and Haithcoat 2005)

Wenbo and his colleagues represented some indices for evaluating the results of automatic building extraction. The represented indices described detection rate, correctness, matched overlay, area omission error, area commission error, root mean square error, corner difference, area difference, perimeter difference and shape similarity for assessing extracted footprints (Wenbo and Haithcoat 2005).

20- (McKeown et al. 2000)

This group introduces some metrics for evaluating feature extraction. These metrics are ‘building detection percentage’, branching factor’ and ‘quality percentage’; and these metrics are computed by the number of four possible categories for each pixel (voxel). These four categories represented as: true positive (TP), true negative (TN), false positive (FP) and false negative (FN) (McKeown et al. 2000). They also represent some metrics for evaluating extracted roads.

Previous paragraphs reviewed different used quality aspects and used methods for assessing that quality aspect by different authors. As it were mentioned, some of the reviewed literatures focused on their reconstruction method and for assessing the results of their method they used some quality aspects; and there were few literatures that their main focus was on quality of 3D building models. The following Table 1 shows quality aspects that used by different authors and list different methods that used for assessing each aspect.

Quality aspects	Assessment method	Proposed by
1. Completeness	a. Visually	(Vosselman and Dijkman 2001) (Akca et al. 2008) (Walter 2007)
	b. Measuring number of extracted segments and wall length in meter.	(Rutzinger et al. 2009a)
	c. Comparing number of extracted building with reference data	(Haithcoat et al. 2001)
	d. Comparing results of assessing two metrics evaluation function by classifying buildings into three classes	(Suveg and Vosselman 2004)
	e. Comparing classification to reference data (Producer's accuracy)	(Pfeifer et al. 2007)
2. Correctness	a. Visually	(Vosselman and Dijkman 2001) (Haithcoat et al. 2001) (Schwalbe 2005) (Walter 2007)
	b. Calculating average and RMS of building parameters	(Suveg and Vosselman 2004) (Wenbo and Haithcoat 2005)
	c. Comparing classification to reference data (User's accuracy)	(Pfeifer et al. 2007)
	d. Checking distance and angle of extracted boundaries	(Cheng and Gong 2008)
3. Number of reconstructed details	a. Visually	(Vosselman and Dijkman 2001)
4. Correctness of reconstructed details	a. Visually	(Vosselman and Dijkman 2001)
5. Geometrical accuracy	a. Measuring RMS	(Haithcoat et al. 2001)
	b. Observing roof geometry shape	(Sargent et al. 2007)
	c. Observing inter building geometry shape	
	d. Observing complete building geometry shape	
6. Roof classification	a. Comparing extracted roofs with reference data	(Haithcoat et al. 2001)
7. Building similarity	a. Measuring overlay error	(Haithcoat et al. 2001) (Rutzinger et al. 2010) (Wenbo and Haithcoat 2005)
	b. Measuring perimeter difference	(Haithcoat et al. 2001) (Wenbo and Haithcoat 2005)
	c. Measuring area difference	
8. Relative positional accuracy	a. Position and dimensions of doors and windows	(Sargent et al. 2007)
9. Absolute positional accuracy	a. Accuracy of highest point of structure	(Sargent et al. 2007)
	b. Accuracy of maximum height of roof ridge	(Sargent et al. 2007)
	c. Accuracy of height of building to base of roof	(Sargent et al. 2007)
	d. Accuracy of ground floor height	(Sargent et al. 2007)
	e. Measuring IQR by using reference points	(Kaartinen et al. 2005)
	f. Measuring IQR for assessing height errors	(Kaartinen et al. 2005)
	g. Measuring IQR for roof elevation accuracy	(Kaartinen et al. 2005)
	h. Measuring least square 3D surface matching	(Akca et al. 2008)
10. Roof inclination accuracy	a. Measuring IQR	(Kaartinen et al. 2005)
11. Footprint check	a. Visually	(Dorninger and Pfeifer 2008) (Keqi et al. 2006)
	b. Observing omission error index	(Keqi et al. 2006) (Wenbo and Haithcoat 2005)
	c. Observing commission error index	
12. Comparing input data and models	a. Do some measurements and showing the results visually and with reference	(Oude Elberink and Vosselman 2010b)

Table 1: Shows assessed quality aspects and used method for assessing them.

As it mention in Table 1, main focus for assessing quality of 3D models were on completeness and correctness of reconstructed sets of 3D models. In next part of this thesis, necessary quality aspects for assessing the quality of individual 3D building model will be represented. The main focus of this thesis is on describing quality of each 3D building models individually, so in this thesis, there is no mention on completeness of whole set(s) of 3D building models.

2.3. Quality aspects

Buildings are one of the considerable parts of each city and building models are important in several city model applications (Oude Elberink 2008). Due to the application requirements, 3D model will be reconstructed in one of the defined LOD's. This paper just thinks of buildings in LOD-2 and LOD-3. Each quality aspects must be defined accurately and threshold of each aspect must be discussed separately in each LOD-2 and LOD-3. Due to the definition and specification of each LOD, quality aspects definitions and thresholds must be discussed.

Buildings usually contains vertical walls and planar roof parts (Oude Elberink 2008). This thesis just mentions buildings with straight lines in their footprints.

So, in this thesis the following assumptions are considered:

- Building models in LOD-2 and LOD-3.
- Building models reconstructed from ALS as input dataset.
- Building models that reconstructed with automatic and semi-automatic method.
- Building models with just straight lines in their footprint (not curve lines).
- Building models with flat roof or sloped roof (not dome-shaped roof).

This paper defined that building body and building roof parts covers the total building surface. Hence for quality control of 3D reconstructed building models individually, the quality aspects of 3D reconstructed buildings will be described in follow:

Quality aspects will be defined in 4 main different groups:

1. Topology of building model
2. Quality aspects related to roof part of building model.
3. Quality aspects related to dormer of building model.
4. Quality aspects related to body part of building model.

Figure 3 shows list of different aspects of quality that must be assess for each individual building model.

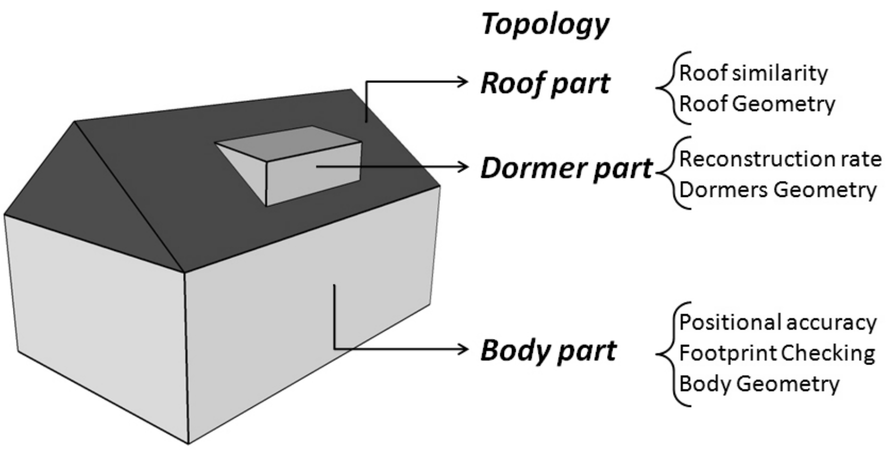


Figure 3: Shows individual reconstructed building model and quality aspects.

As it is shown in Figure 3, for each part of building models (roof and body) various quality aspects were introduced. In the following, each of the above aspects will be defined and described briefly:

2.3.1. Topology check

Topology means spatial relationship between objects (Devillers and Jeansoulin 2006) and topology usually used for describing the connectivity of an n-dimensional graph (2009b). Each 3D object in 3D space consists of following components (Molenaar 1992):

1. Body: in this thesis define as individual 3D building model that contains body part and roof part.
2. Surface-object: in this thesis introduced as wall, roof and dormer faces.
3. Line-object: line segments of each face.
4. Point-object: end nodes of each line segment.

Components of 3D building model are shown in Figure 4.

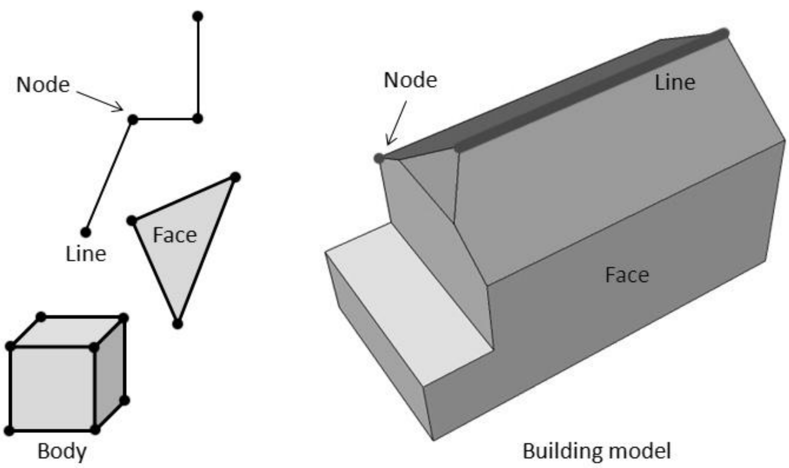


Figure 4: Shows components of 3D object in 3D space.

Each 3D model has topological consistency if topological characteristics of a 3D model encoded correctly (2002). For each individual 3D building model, topology will be consistent when:

- Intersection of two line segments has node.
- Each straight line segment has two end nodes.
- Poly-lines should be connected to each other (2002) and creates closed polygon.
- Each close polygon defined as face (wall face, roof face or dormer face).
- There were no empty space or open polygons between faces.
- Body must consist from continues faces and doesn't has any holes or empty spaces.

For each 3D building model, if the above conditions be implemented then that model has topological consistency.
As in mention before, this thesis just focused on LOD-2 and LOD-3; and interior of 3D building models is not important, so for topology check, just mention on crust surface of 3D building body is sufficient.

Topology check is one important factor for quality description of a 3D building model and for checking topology of 3D building models there is no need to have reference dataset. In the following, Figure 5 shows some example of 3D building models with no topological consistency.

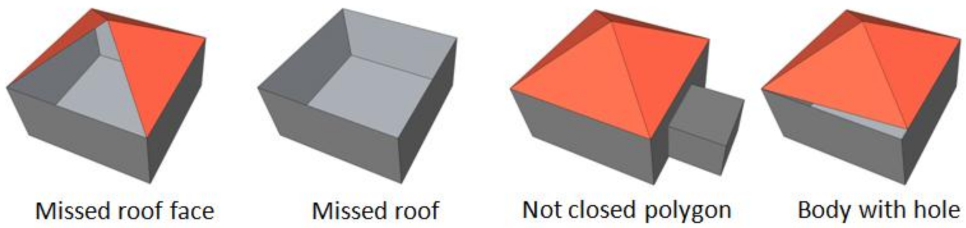


Figure 5: Shows example of some 3D building models with no topological consistency.

2.3.2. Quality aspects related to roof part

Quality aspects related to roof part of a model assessed just for sloped roofs, and there is no need to assess the following aspects for flat roofs. Quality of flat roof buildings will be mention and described just by the body part of 3D model. For sloped roof two different quality aspects will be define in the following:

2.3.2.1. Roof similarity

Before describing roof similarity as an aspect for assessing the quality of 3D model in roof part, roof face and roof node must be defined:

- Roof face:

Each closed polygon has line segments and nodes that represents an face area (de By et al. 2001), each face in 3D space has some orientation parameters.

Roof face defined as sloped face of buildings (not vertical or horizontal). Because in automatic and semi-automatic methods for 3D reconstruction, walls defined as vertical face of building and flat roofs are always horizontal.

Each building with sloped roofs has minimum one roof face. Figure 6 shows one flat roof building and some example of different buildings with sloped roofs and number of their roof faces.

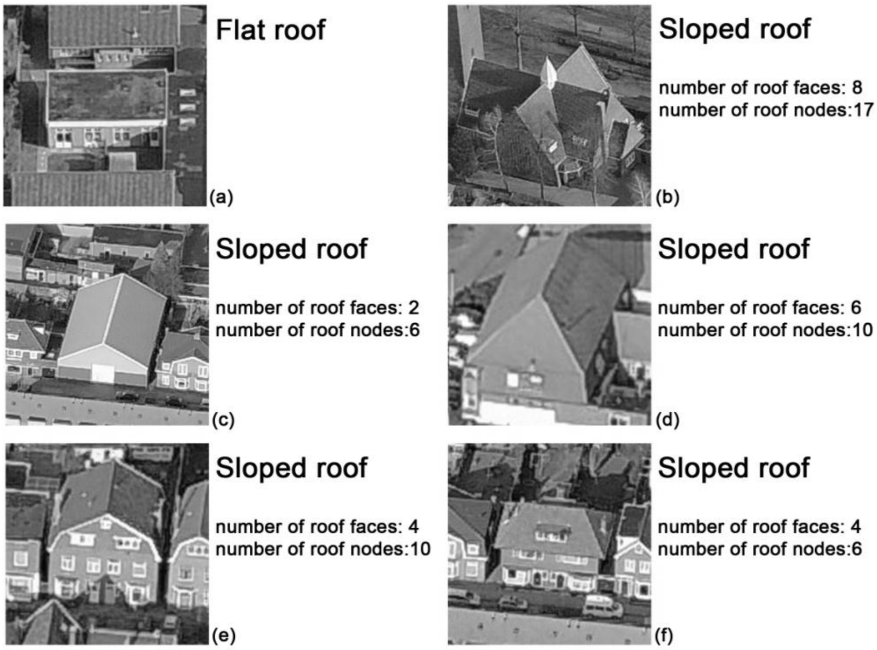


Figure 6: Shows 5 example of sloped roof buildings and number of their roof faces.

Dormers are also sloped faces, but because they have smaller sloped face in comparison to roof faces and also they are inside roof faces, assessing and mention on their quality will be described in quality aspects related to dormers part.

- Roof nodes:

Intersection of two roof faces is a line with two end nodes (de By et al. 2001). In this thesis these end nodes are used as roof nodes and each of these nodes has its own location in X, Y and Z coordinates. Meanwhile, intersections of more than two roofs faces produce more than one segment line and ore roof nodes.

3D model has roof similarity in comparison to reference dataset, if, the roof shape of 3D model be same as roof shape of building in reference. That means, number of roof faces must be same in both 3D model and reference dataset; in addition, the position (X, Y and Z values) of each roof nodes in 3D model must be same in comparison to the corresponding roof node in reference dataset. Due to using ALS as input dataset permissible thresholds between position of two corresponding nodes must be less than 35cm for X and Y values and 30 cm for Z value (Oude Elberink and Vosselman 2010b).

Therefore, for roof similarity of 3D building model, first, number of roof faces in 3D model must be compared by reference. If they aren't equal, 3D model hasn't got similarity in roof part. But if number of roof faces is same in 3D model and reference, then number of roof nodes of 3D model and position of these nodes must be compared with reference. If they are equal and also their positions are in defined threshold, then the roof of 3D model is similar and if not there isn't similarity in roof shape of 3D model in comparison with reference. Figure 7 shows flowchart of steps for assessing this quality aspect with Unified Modelling Language (UML) (D'Souza and Wills 1999),(Arlow and Neutze 2001).

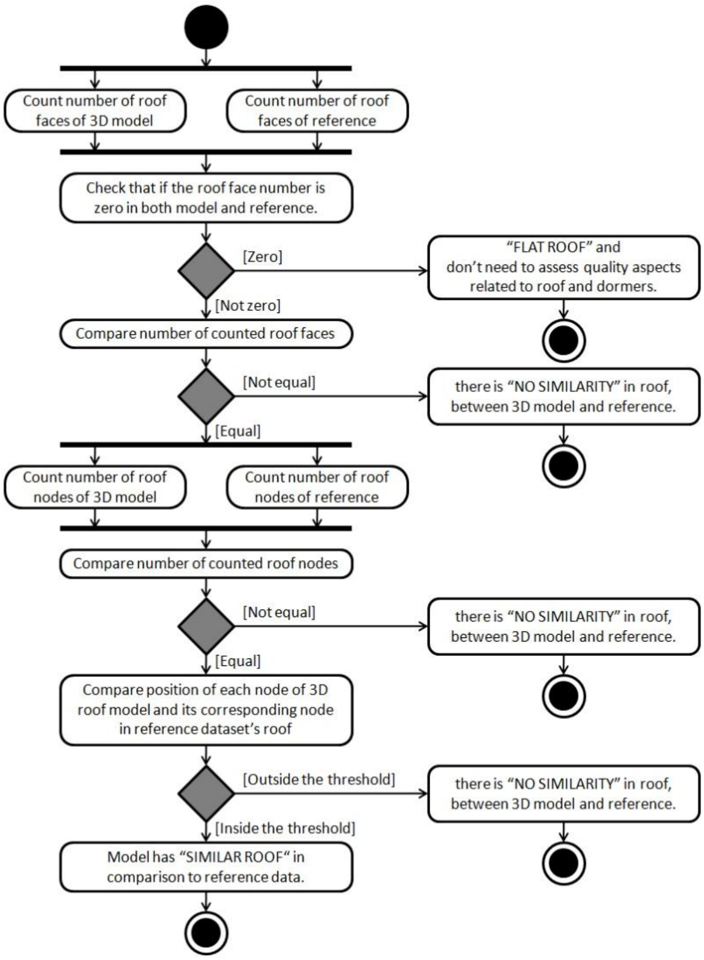


Figure 7: Shows method for assessing roof similarity aspect with UML.

Figure 8 shows an example of real building with 3 roof faces and 6 roof nodes in reality and 7 examples for reconstruction model. In first stage, by comparing roof faces between models and real building, it will be determined that model C has not similarity in roof part with real building. Though models B, D and E have equal roof faces in comparison with real building, but due to differ between their roof nodes and roof nodes of real building, these models also have not similarity in roof part with real building. Models F and G have equal number of roof faces and roof nodes in comparison to real building. But they are also haven't similarity in roof part with real building because the position of node 1 in model G and also position of nodes 1 and 2 in model F are not in defined permissible thresholds. As it is shown in this Figure 8, just model A has similarity in roof part with real building, because number of roof faces and number of roof nodes are equal with real building; and in addition, the position of all roof nodes are in permissible threshold.

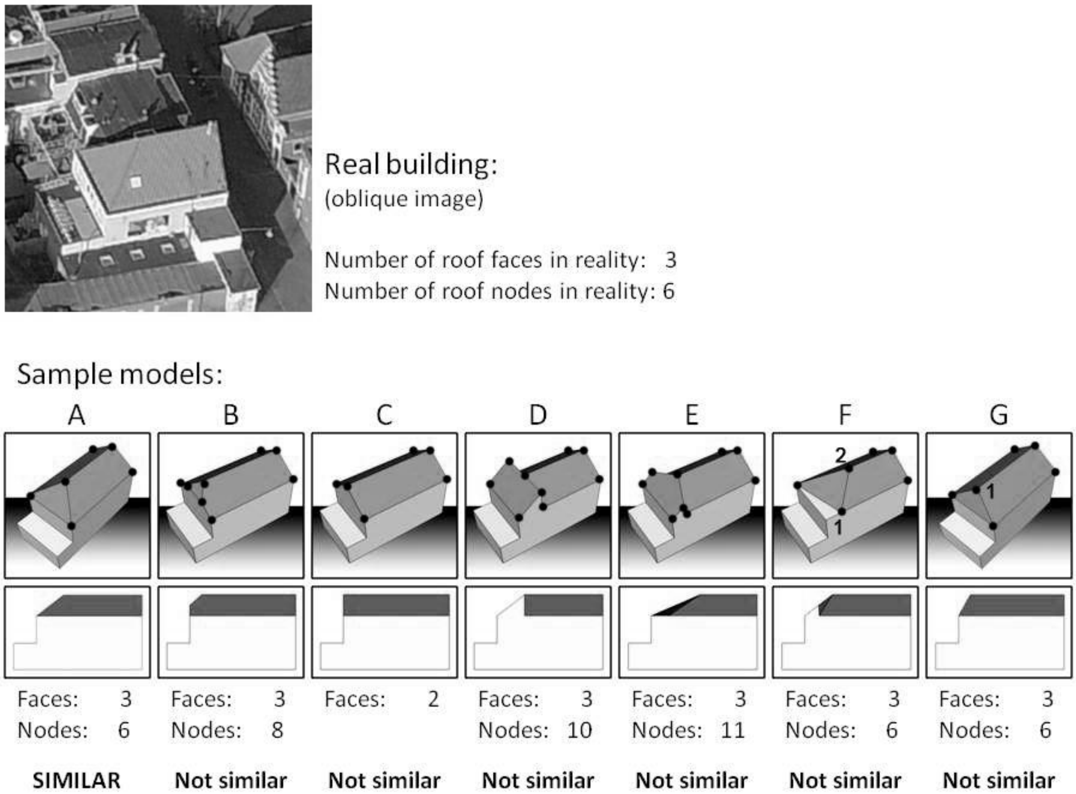


Figure 8: Shows some example of models with different reconstructed roofs.

For assessing roof similarity in chapter 4 of this thesis, the position of roofs nodes were not mentioned as accurate that is described here. Roof similarity will be assessed in chapter 4 by visually comparing shape of 3D model's roof and roof shape in reality (reference). So, in this case, as it were shown in Figure 8, B and G will be also listed as similar roofs. Because of some generalizations in LOD-2, building model B and G also will be assessed as models with roof similarity in this thesis.

2.3.2.2. Geometry of roof part

Quality aspects related to geometry of roofs are height accuracy and inclination precision. In the following both height and inclination precision will be introduced:

A. Height accuracy:

Height accuracy means calculating differences of roof's height between roof part of 3D model and roof part of building in reference. Height of roof defined as vertical distance between the lowest node of roof and the highest node of roof. Figure 9 shows an elevation of 3D building model and roof height (H1) of it.

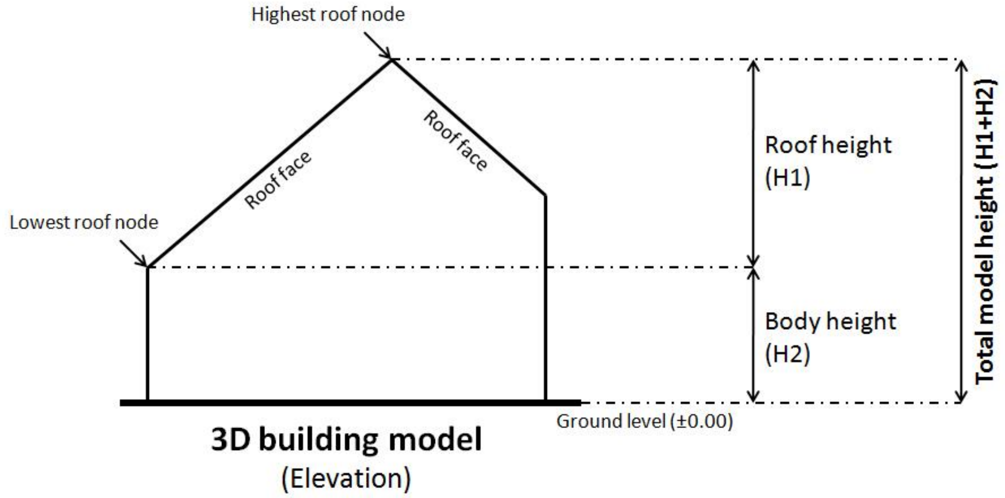


Figure 9: Shows roof height of 3D model as a difference between vertical values of the lowest and highest nodes of roof part.

In this case for choosing the highest node, if there were horizontal ridge in 3D model's roof, each nodes of that ridge can be defined as highest node and the inclination of roof's ridge is zero (Sargent et al. 2007). But if ridge of 3D model (or building in reference) is not horizontal and 3D model (or building in reference) has sloped roof ridge, roof ridge inclination is also measurable and roof's ridge inclination precision can be defined as another quality aspect related to quality of roof parts. Figure 10 shows 3 sample 3D models with various kinds of roof ridges.

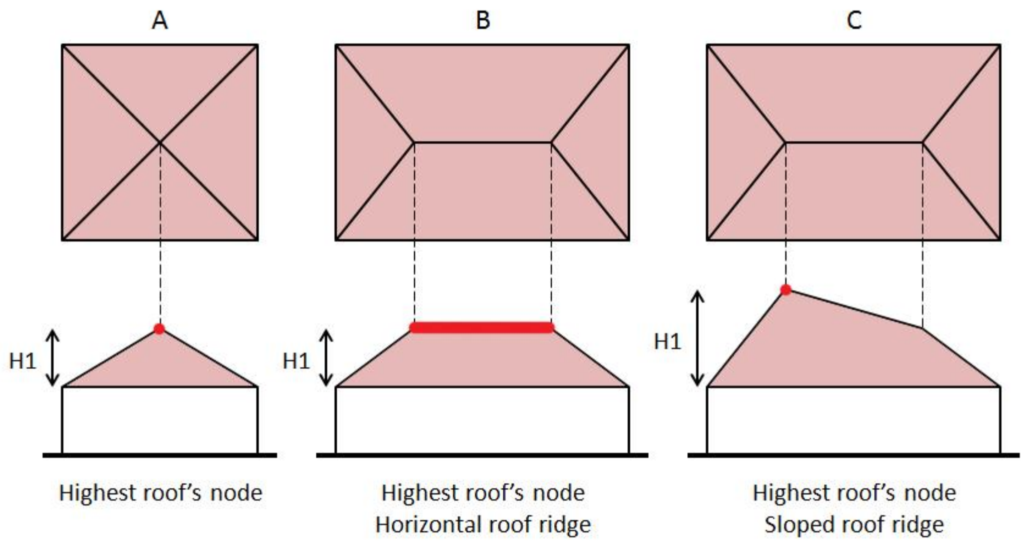


Figure 10: Shows roof plan and elevation of three sample models, model 'a' just has highest point, model 'b' and 'c' has roof ridge and in model 'c', roof ridge also has inclination. Red colours are highest points of roofs.

As it were mentioned before, height accuracy of 3D model introduce as difference between vertical distance of highest and lowest roof nodes in 3D model and corresponding distance in building from reference. The following Figure 11 shows workflow of assessing height accuracy of 3D model's roof with UML:

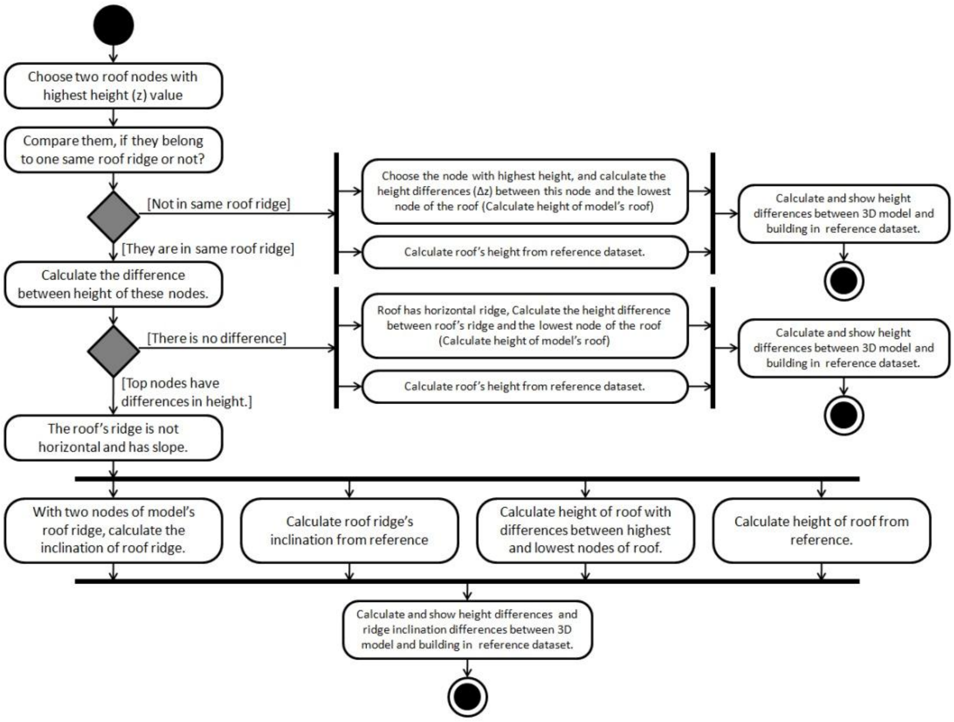


Figure 11: Shows workflow of assessing height accuracy and roof ridge inclination.

B. Inclination (slope) precision:

Calculating root mean square error (RMSE) for comparing differences between roof slopes of 3D model's faces and roof slopes of building's faces in reference is one of the quality aspects of geometry of roof part.

If 3D model has n faces, then calculating slope of each face will be possible with position of the lowest point and position of the highest point of each face. In this case, θ1 will be set of n values of roof face's slopes of 3D model. On the other hand, by calculating slope of each roof face from building in reference θ2 will be set of n values of roof face's slopes of building in reference.

$$\textbf{3D Model's roof slopes}: \quad \boldsymbol{\theta 1} = \{\boldsymbol{\alpha_{1,1}}, \boldsymbol{\alpha_{1,2}}, \dots, \boldsymbol{\alpha_{1,n}}\}$$

$$\textbf{Real building's roof slopes}: \boldsymbol{\theta 2} = \{\boldsymbol{\alpha_{2,1}}, \boldsymbol{\alpha_{2,2}}, \dots, \boldsymbol{\alpha_{2,n}}\}$$

RMSE of roof inclination can be calculating from two set of n values θ1 and θ2:

$$\textbf{RMSE}\,(\boldsymbol{\theta 1}, \boldsymbol{\theta 2}) = \sqrt{\frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} (\boldsymbol{\alpha_{1,i}} - \boldsymbol{\alpha_{2,i}})^{2}}{\mathbf{n}}}$$

Calculating RMSE between slopes of roof faces in 3D model and building in reference will be useful as one of the quality descriptions of 3D building model that related to geometry of roof part of 3D model. In the following, Figure 12 shows flowchart of steps for assessing this quality aspect with Unified Modelling Language (UML):

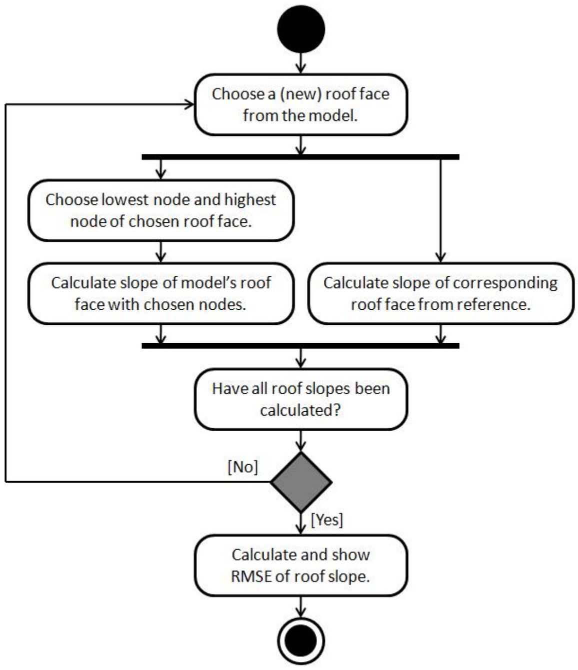


Figure 12: Shows flowchart for calculating RMSE of roof face slopes with UML.

2.3.3. Quality aspects related to dormer part

A dormer is one of the roof extensions that extrude from the sloped roof face, and has smaller dimensions (smaller faces) in comparison with the roof face that extrude from. Dormers are constructed in various shapes and forms, as it is shown some example of different dormers in the following Figure 13:

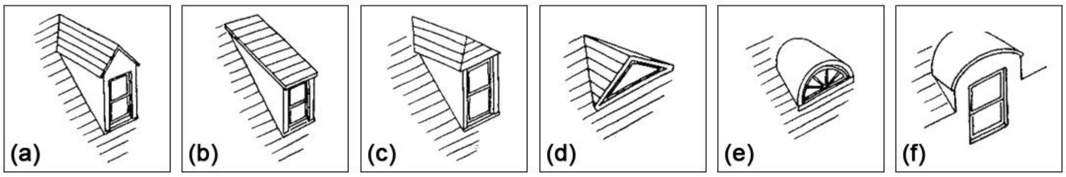


Figure 13: Shows some examples of various roof dormers' shape.

Assessing the quality of reconstructed dormers in 3D building models are interesting, and knowing about quality description of reconstructed dormers may be useful for some users. This thesis mentions on reconstruction rate of dormers and dormers geometry check as quality aspects related to dormer's part. In the following both reconstruction rate and geometry of dormers will be defined briefly:

2.3.3.1. Dormer's reconstruction rate

By comparing number of reconstructed dormers in 3D model and number of available dormers of building in reference dataset, assessing dormer's reconstruction rate will be possible.

$$\text{Reconstruction Rate} = \frac{\text{number of reconstructed dormers of 3D model}}{\text{number of available dormers of building in R. D.}} * 100$$

If dormers were available in 3D model or building in reference, then by selecting dormer's roof faces, counting dormers will be possible in both 3D model and building in reference. Dormers roof faces must have smaller dimensions in comparison with roof faces that they extrude from. Each individual dormer may have one face for its roof (example: Figure 13, b) or have more than one face for its roof (example: Figure 13, a, c and d). In the case of having more than one face for dormer's roof, selected faces must be continuous and have joint borders. In this case these faces consists one individual dormer's roof.

In the following Figure 14 shows flowchart of steps for assessing this quality aspect with Unified Modelling Language (UML) and Figure 15 shows example of dormer's reconstruction rate by comparing reconstructed dormers in 3D model and available dormers of building in reference dataset (in this example reference dataset is oblique images).

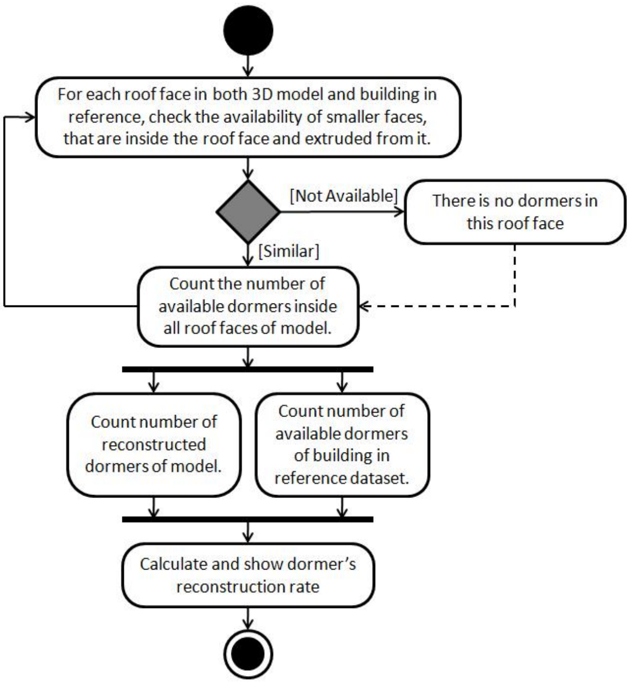
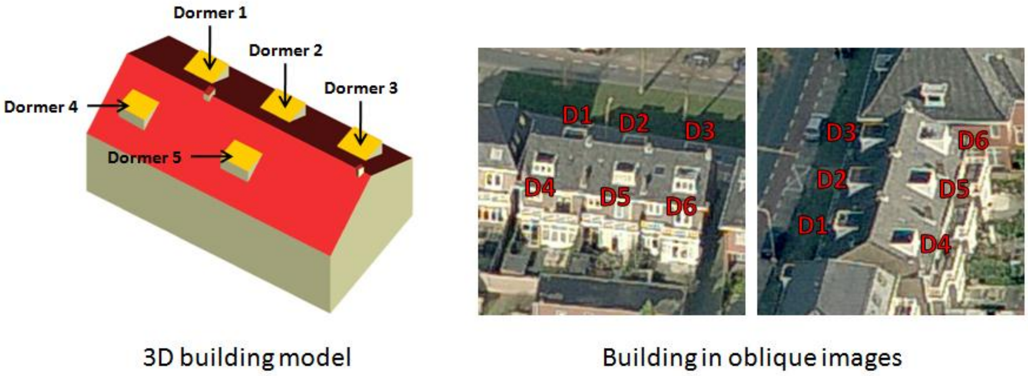


Figure 14: Shows flowchart for dormer's reconstruction rate with UML.



Number of reconstructed dormers: 5

Number of available dormers of building in reference: 6

$$\text{Dormer's reconstruction rate of this 3D building model} = \frac{5}{6} = 83.3\ \%$$

Figure 15: Shows an example of dormer's reconstruction rate.

If the result of dormer's reconstruction rate was zero, then isn't need for checking dormer's geometry. But in case of reconstructed dormer(s), checking geometry of reconstructed dormer(s) is one of the dormer's quality aspects.

2.3.3.2. Dormer's geometry check

A. Height accuracy:

As it were mentioned before, various types of dormers are available (as examples of Figure 13). In this thesis, height of dormers defined as vertical distance between lowest node and highest node of front façade of dormers and this thesis doesn't mention on other faces for height of the dormers. Figure 16 shows height of dormers when: (a) dormer has flat roof, (b) dormer has one slope roof, (c) dormer has complicated sloped roof.

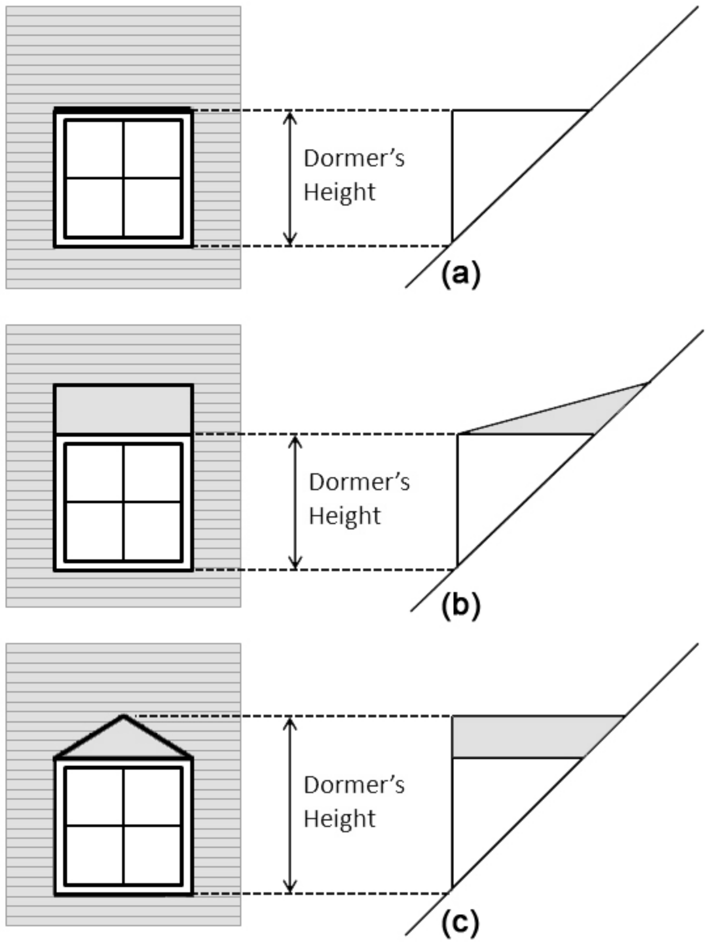


Figure 16: Shows height of different types of dormer. Roof (a) shows dormer with flat roof, roof (b) and (c) shows dormers with sloped roof.

Calculating root mean square error (RMSE) for comparing differences between heights of reconstructed dormers and corresponding heights of dormers in reference is one of the quality aspects of geometry of dormer part.

$$\textbf{Heights of reconstructed dormers}: \quad \boldsymbol{\theta}\mathbf{1} = \{\mathbf{h_{1,1}}, \mathbf{h_{1,2}}, \dots, \mathbf{h_{1,n}}\}$$

$$\textbf{Corresponding heights in reference}: \quad \boldsymbol{\theta}\mathbf{2} = \{\mathbf{h_{2,1}}, \mathbf{h_{2,2}}, \dots, \mathbf{h_{2,n}}\}$$

RMSE of dormer's height can be calculating from two set of n values θ1 and θ2:

$$\mathbf{RMSE}\ (\boldsymbol{\theta}\mathbf{1}, \boldsymbol{\theta}\mathbf{2}) = \sqrt{\frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{h_{1,i}} - \mathbf{h_{2,i}})^2}{\mathbf{n}}}$$

In the following, Figure 17 shows flowchart of steps for assessing this quality aspect with Unified Modelling Language (UML):

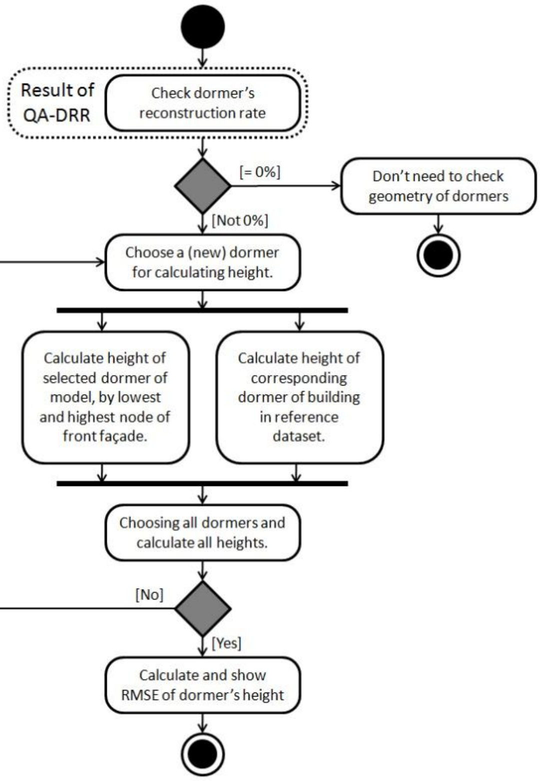


Figure 17: Shows flowchart of calculating RMSE of dormer's height with UML.

B. Length accuracy:

One of the other geometry checks for reconstructed dormers is dormer's length accuracy. In this thesis, length of dormer defined as horizontal distance between two vertical lateral faces of dormer. Figure 18 shows an example of dormer's length that restricted between two vertical faces of dormer.

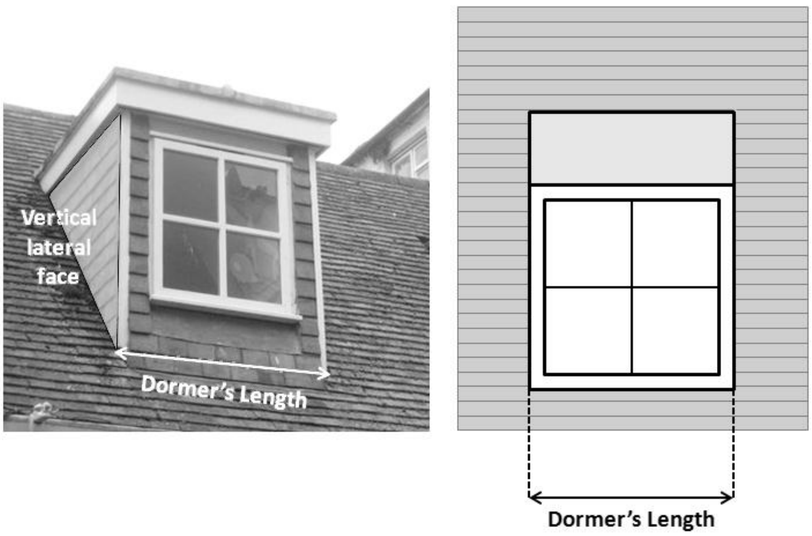


Figure 18: Shows dormer's length.

Calculating root mean square error (RMSE) for comparing differences between lengths of reconstructed dormers and corresponding lengths of dormers in reference is one of the quality aspects of geometry of dormer part.

$$\textbf{Lengths of reconstructed dormers}: \quad \boldsymbol{\theta 1} = \{\mathbf{l_{1,1}}, \mathbf{l_{1,2}}, \dots, \mathbf{l_{1,n}}\}$$

$$\textbf{Corresponding lengths in reference}: \quad \boldsymbol{\theta 2} = \{\mathbf{l_{2,1}}, \mathbf{l_{2,2}}, \dots, \mathbf{l_{2,n}}\}$$

RMSE of dormer's length can be calculating from two set of n values θ1 and θ2:

$$\mathbf{RMSE}\ (\boldsymbol{\theta 1}, \boldsymbol{\theta 2}) = \sqrt{\frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{l_{1,i}} - \mathbf{l_{2,i}})^2}{\mathbf{n}}}$$

In the following, Figure 19 shows flowchart of steps for assessing this quality aspect with Unified Modelling Language (UML):

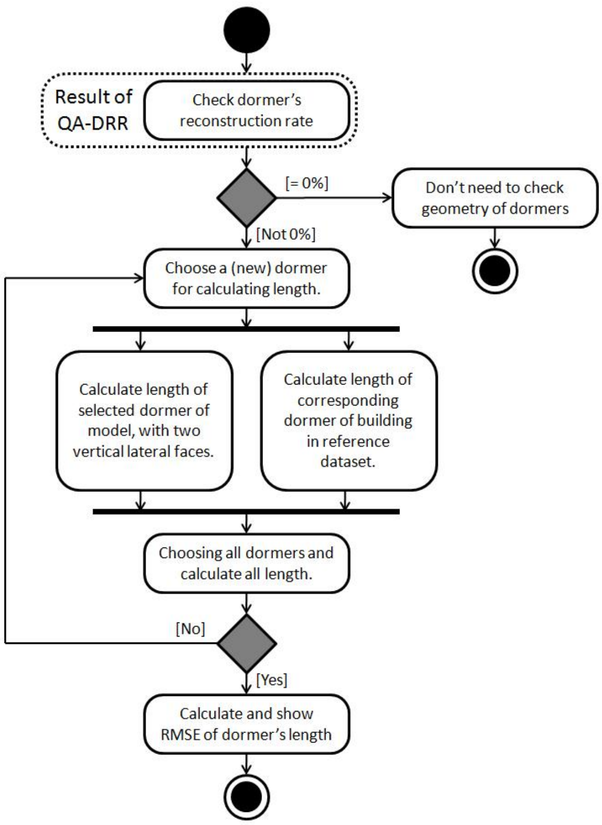


Figure 19: Shows flowchart of calculating RMSE of dormer's length with UML.

2.3.4. Quality aspects related to body part

For assessing quality of 3D model's body part, positional accuracy, footprint similarity, body height accuracy will be described in the following. Positional accuracy and footprint checking are aspects that describe whole model's position and shape and in this case, some indices will be introduced.

2.3.4.1. Positional accuracy

Positional accuracy defined as: "accuracy of the position of features" (Devillers and Jeansoulin 2006). In Figure 20, there is an example of position of one node (point) from 3D model in XY coordinates and shows X and Y difference and distance of it from corresponding point in reference (true position) (Caspary and Scheuring 1993).

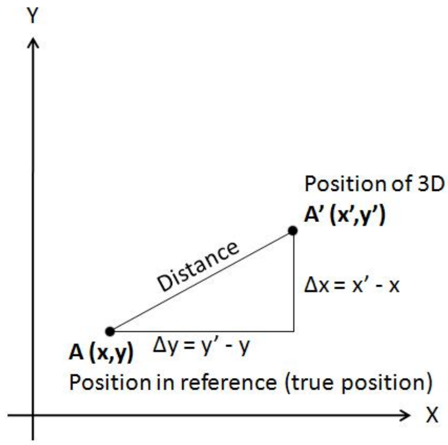


Figure 20: Shows differences in X and Y values between two corresponding nodes.

In this thesis, assessing positional accuracy of each individual 3D building model will be describes in the following:

For comparing corner nodes of 3D model and building in reference, central points of them must be in same planar coordinates; and reference dataset and 3D model must have a comparable level of details. For each corner nodes of 3D model's footprint, the nearest corresponding corner node (point) in reference must be choose and differences in X values and Y values and distance between these two corresponding nodes must be measured; after that, by calculating RMS for distance between all corner nodes and their corresponding corner nodes, and RMSE for X differences and RMSE for Y coordinates, assessing positional accuracy will be possible (Wenbo and Haithcoat 2005). In the following, Figure 21 shows 3D model and its reference and comparison between their corner nodes for assessing the positional accuracy. And Figure 22 will show flowchart of steps for assessing positional accuracy of 3D model with Unified Modelling Language (UML):

$$\textbf{X value of 3D model's corner nodes:} \qquad \boldsymbol{\theta 1 = \{x_1, x_2, \dots, x_n\}}$$
$$\textbf{X value of cooresponding nodes in reference:} \quad \boldsymbol{\theta 2 = \{x'_1, x'_2, \dots, x'_n\}}$$

$$\mathbf{RMSE\ (\theta 1, \theta 2) = RMSE\ X} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - x'_i)^2}{n}}$$

$$\textbf{Y value of 3D model's corner nodes:} \quad \theta 3 = \{y_1, y_2, \ldots, y_n\}$$

$$\textbf{Y value of cooresponding nodes in reference:} \quad \theta 4 = \{y'_1, y'_2, \ldots, y'_n\}$$

$$\mathrm{RMSE}\ (\theta 3, \theta 4) = \mathrm{RMSE\ Y} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y'_i)^2}{n}}$$

$$\textbf{Distance between two nodes:} \quad d = \sqrt{(x - x')^2 + (y - y')^2}$$

$$\textbf{Distance between cooresponding nodes:} \quad \theta 5 = \{d_1, d_2, \ldots, d_n\}$$

$$\mathrm{RMS}\ (\theta 5) = \mathrm{RMS\ distance} = \sqrt{\frac{\sum_{i=1}^{n}(d_i)^2}{n}}$$

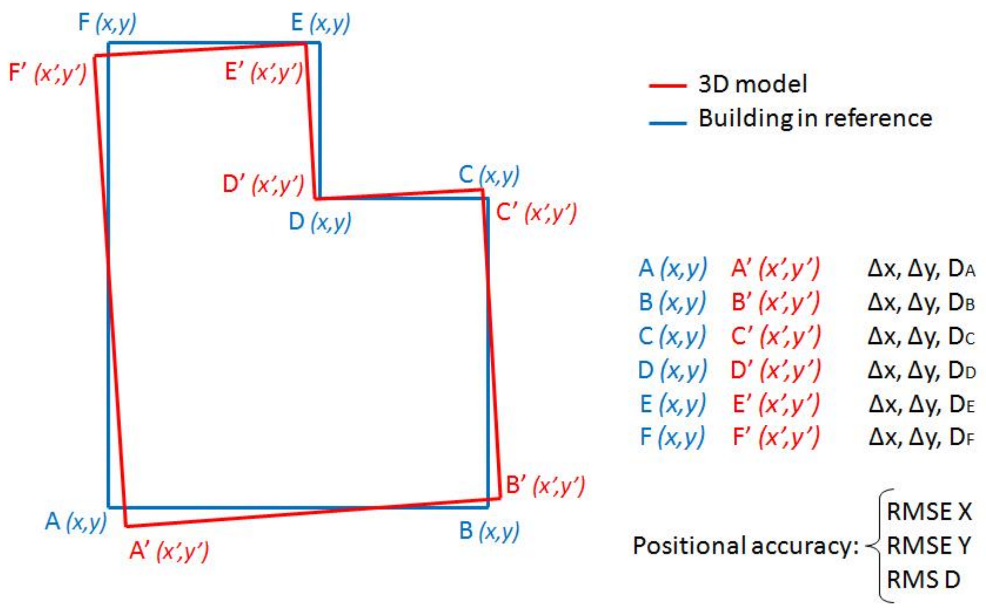


Figure 21: Shows example of 3D model and reference and comparison their corner nodes for assessing positional accuracy of 3D model.

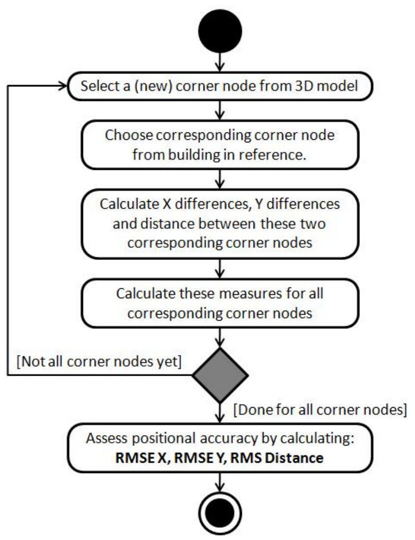


Figure 22: Shows positional accuracy assessment flowchart in UML.

2.3.4.2. Footprint correctness and related indices

Footprint defined as building's boundary (outline of building). Building footprints in 3D models may be necessary for various applications such as real estate industry, flood management, home land security and 3D city models (Cheng and Gong 2008). In this thesis, by using some indices, assessing quality of 3D model's footprint will be possible. Each footprint contains nodes (building corners) and line segments, and these continuous line segments create a closed polygon named building footprint. Presented indices will be grouped into three levels (Wenbo and Haithcoat 2005); and results will be mentioned on quality description of 3D model. In the following, each index will be described briefly:

- Footprint correctness:

One objective of this thesis is to reconstruct 3D models in LOD-2, therefore, minimum dimensions of body parts that expected to reconstruct in 3D model will be 3 meter to 3 meter (3mX3m), and so building parts with less than this dimensions will not be reconstructed. So, before checking models with any reference , these types of body parts must be remove from reference dataset (Pfeifer et al. 2007), that means, reference dataset and 3D model must have a comparable level of details. Figure 23, shows on example of removing small objects from reference dataset before using it.

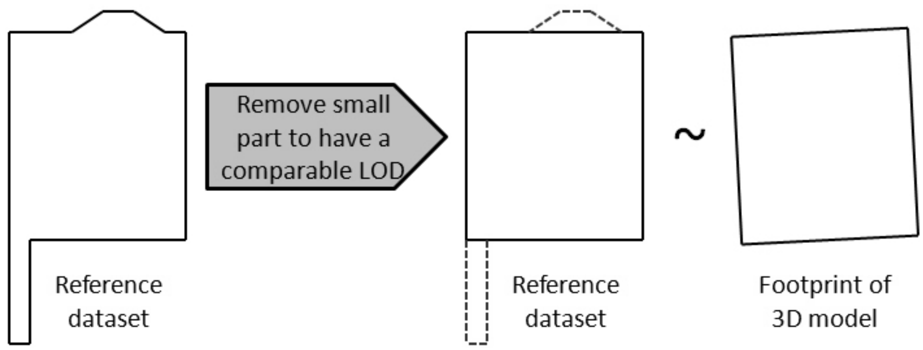


Figure 23: Shows example of reference dataset and 3D model's footprint that have comparable level of details.

In this thesis, for each individual 3D model, its footprint will be correct if:

1. Number of line segments in footprint of 3D model and reference dataset are equal (again mention that reference and 3D model must have a comparable level of details).

2. Calculating the length differences between each line segment from 3D model's footprint and its corresponding line segment in reference. In this case, the RMS for length differences between all line segments of 3D model and reference must be less than 50cm (Cheng and Gong 2008).

$$\textbf{Line segments length differences}: \quad \Delta\mathbf{L} = \{\mathbf{l_1}, \mathbf{l_2}, \ldots, \mathbf{l_n}\}$$

$$\mathbf{RMS}\ (\Delta\mathbf{L}) = \sqrt{\frac{\sum_{i=1}^{n} \mathbf{l_i}^2}{\mathbf{n}}} \leq \mathbf{50\ cm}$$

3. Calculating the angle between each line segment of 3D model's footprint and its corresponding line segment in reference, by putting central point (Rutzinger et al. 2009c) of 3D model's footprint and central point of footprint of building from reference in same planar coordinates. In this case, the RMS for angle of all line segments in 3D model and reference must be less than 3 degrees (Cheng and Gong 2008).

$$\textbf{Line segments angle differences}: \quad \boldsymbol{\Delta\alpha = \{\alpha_1, \alpha_2, \dots, \alpha_n\}}$$

$$\mathbf{RMS\ (\Delta\alpha)} = \sqrt{\frac{\sum_{i=1}^{n} \alpha_i^{\,2}}{n}} \ \leq \mathbf{3\ degrees}$$

Figure 24, shows example of footprint of 3D model and reference is compared when central points of them are in same planar coordinates.

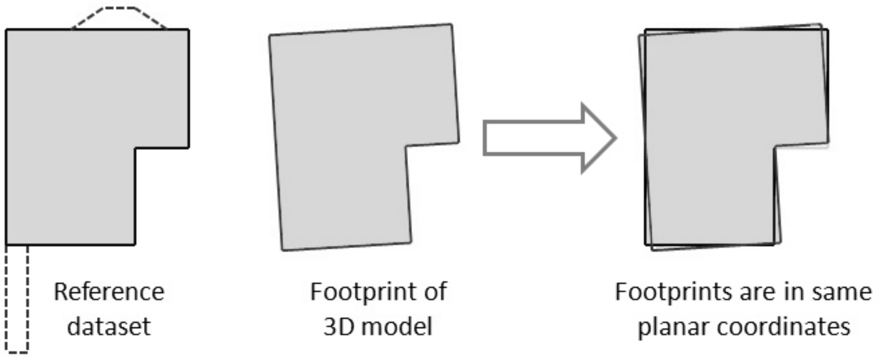


Figure 24: Shows an example of model's footprint and reference footprint in same planar coordinates for calculating RMS of angle differences and distance differences.

If all of three above conditions were observed, then the 3D model's footprint will treated as correct. The following Figure 25 shows flowchart of steps for assessing that the model has correct footprint or not with Unified Modelling Language (UML):

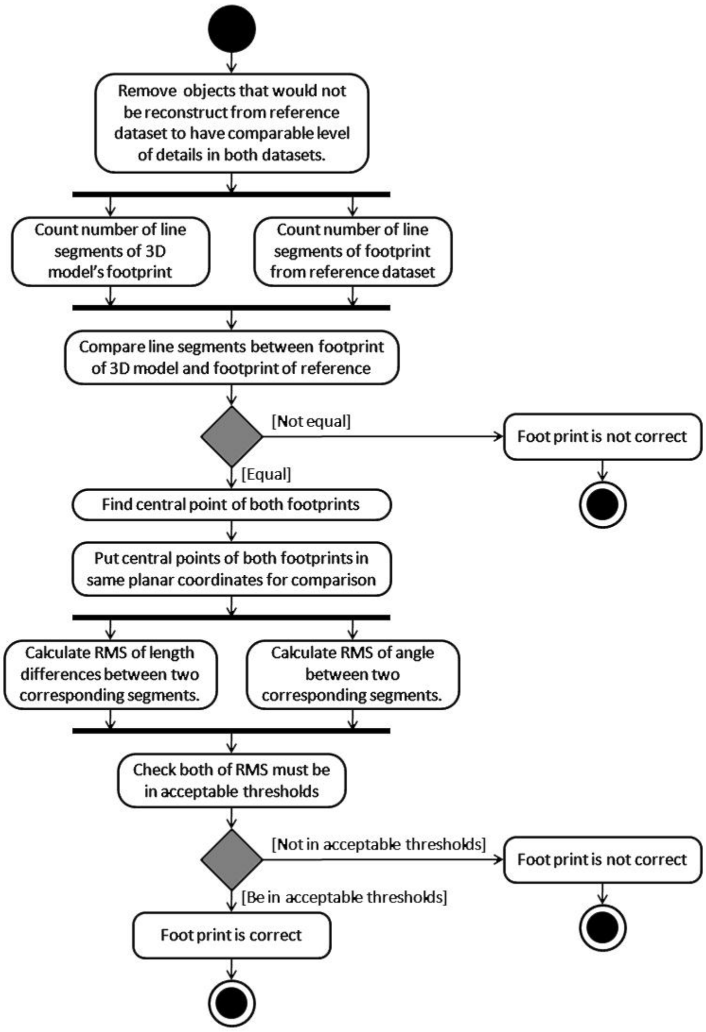


Figure 25: Shows footprint correctness assessment flowchart in UML.

Furthermore that the footprint is correct or not in comparison to reference, some other indices must be calculated for assessing the model's footprint. These indices related to comparing the footprint's area in both datasets and for shape similarity. In the following, these indices will be introduces:

- Area-based indices:

With comparison of 3D model's footprint and footprint of reference dataset for each building individually, the following indices can be calculated as quality descriptions of 3D model's footprint:

- Matched overlay: dividing total overlapped area to total area of reference footprint represents percentage of correctly extracted building parts (Wenbo and Haithcoat 2005).
- Area omission error: dividing area of non extracted parts to total area of reference footprint represents amount of building parts that are not detected (Wenbo and Haithcoat 2005).
- Area commission error: dividing area of incorrectly extracted parts to total area of 3D model's footprint represents amount of incorrect extracted building parts (Wenbo and Haithcoat 2005).

The following Figure 26 shows matched overlay, area omission and commission errors of 3D model's footprints in comparison to reference. And Figure 27 shows flowchart of steps for calculating these indices for quality descriptions of 3D model's footprint in Unified Modelling Language (UML):

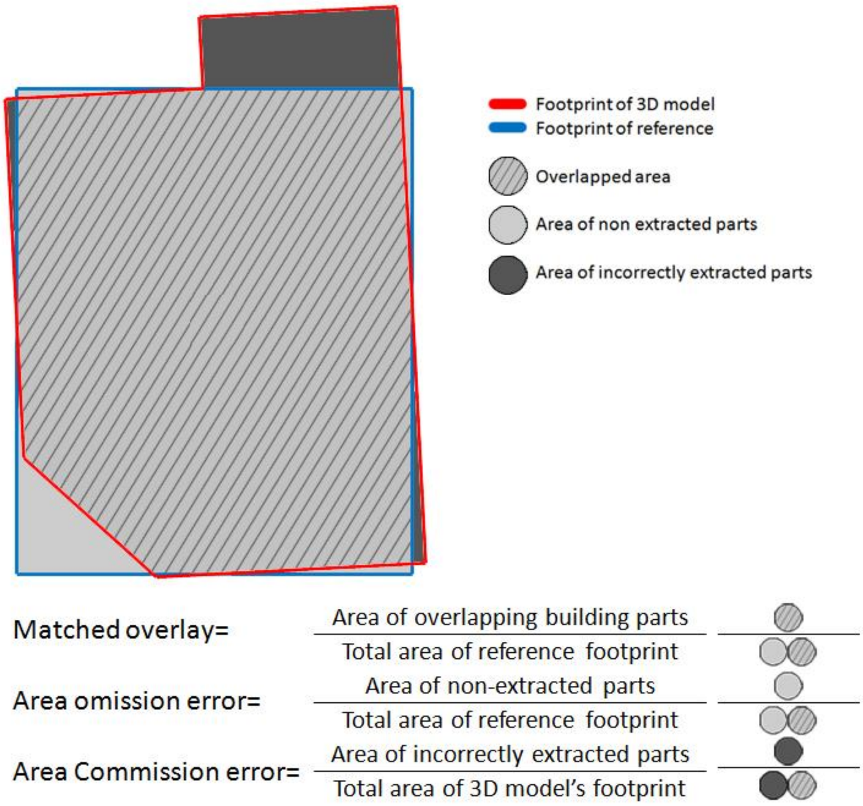


Figure 26: Shows matched overlay, area omission and commission errors of footprint in model and reference.

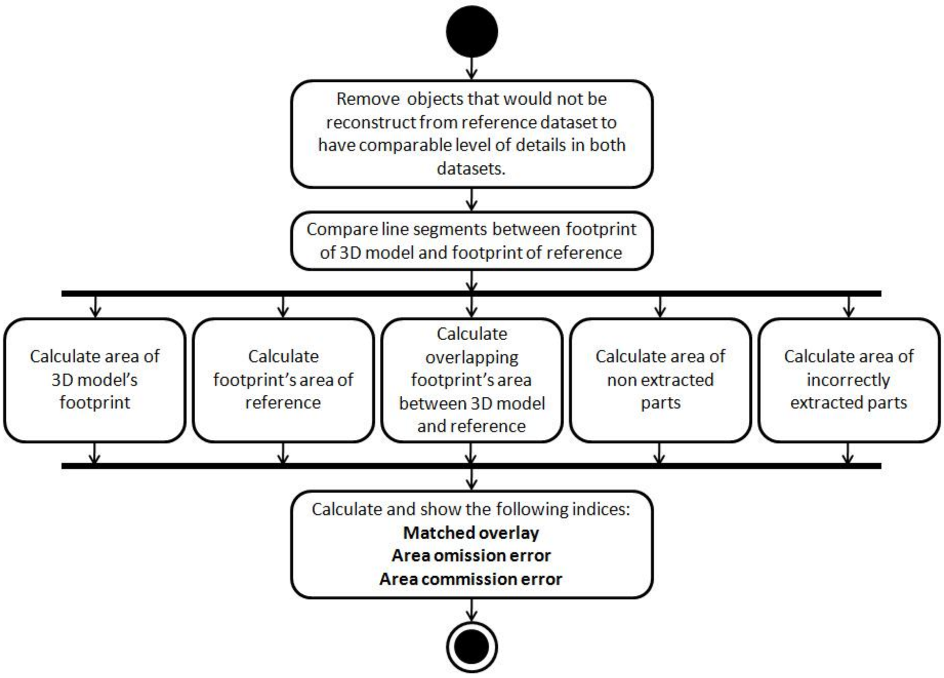


Figure 27: Shows flowchart for calculating footprint indices in UML.

- Shape similarity indices:

For shape similarity the following indices will be introduced:

  - Area difference: absolute area difference between model's footprint and reference divided by area of reference.

  - Perimeter difference: absolute perimeter difference between model's footprint and reference divided by perimeter of reference.

In the following, Figure 28 shows flowchart of steps for calculating these indices for quality descriptions of 3D model's footprint in Unified Modelling Language (UML):

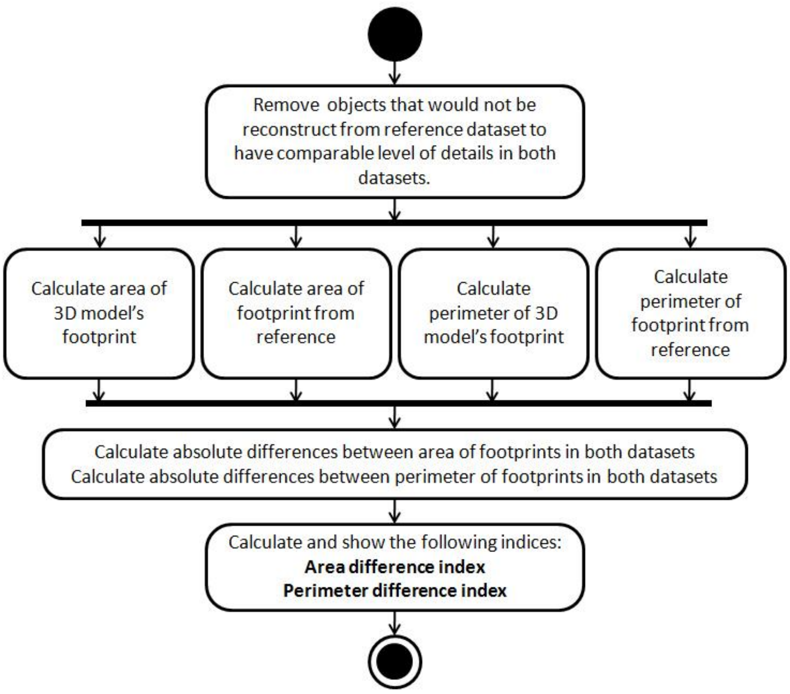


Figure 28: Shows flowchart for calculating footprint indices in UML.

Therefore, the above indices will describe quality of 3D model's footprint. Either the 3D model's footprint is correct or not, these five indices must be calculated for assessing the quality of 3D model's footprint.

2.3.4.3. Height accuracy of body part

As it is shown in Figure 9, in this thesis, height of building's body defined as vertical distance (height differences) between lowest node of the roof and ground level (Sargent et al. 2007). If there was a flat roof, the difference between height of highest node of the model and height of ground level will be the height of building model.

After measuring body height of 3D model, by comparing that height to measured body height from reference, two following indices will be prepared:

- Height accuracy: difference between body height of 3D model and body height of reference.

- Absolute height difference: percentage of absolute difference between body height of 3D model and body height of reference divided by body height in reference.

These two indices also can be calculated for total height of building model (body part and roof part, H1+H2 in Figure 9). In the following, Figure 29 shows flowchart of steps for calculating these indices for quality descriptions of body height of 3D model in Unified Modelling Language (UML):

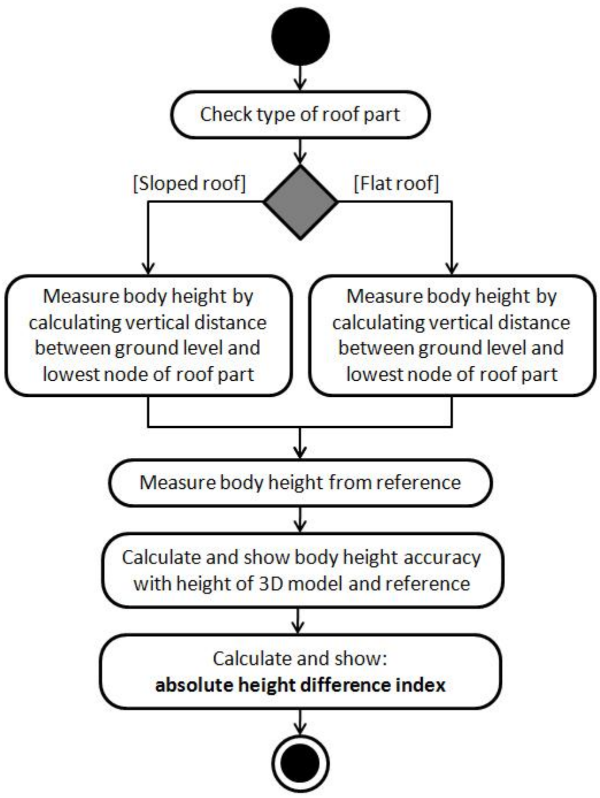


Figure 29: Shows flowchart for assessing body height indices in UML.

In this section, aspects that related to quality of 3D models described briefly. As it mentions, due to main parts of building models (roof, dormer and body), quality aspects divides into three groups. In the following section, preparing quality report for each individual building model by assessing defined quality aspects will be described.

2.4. Quality report

With respect to the proposed quality aspects and related indices that were described in previous part of this chapter, preparing quality report will be possible. By assessing the proposed quality aspects and measuring related indices quality report will be prepared. As it mention in previous part, assessing quality aspects and related indices will be described 3D model's quality. In addition, choosing reference dataset from available datasets and quality of chosen reference dataset for each quality aspect is important part for preparing quality report, and has effect on quality report. Reference datasets and quality of them will be described in the following chapter 4.

Main idea of this thesis is need for preparing (having) quality report for each individual 3D building model for describing quality of each model by assessing proposed quality aspects and related indices. So, by preparing quality report for each 3D building model, preparation of quality report for whole 3D model set will be possible. Besides, by having quality report of some sample 3D building models in set of 3D models, estimating quality of whole set will be possible.

On the other hand, users of 3D building models, due to their requirements, needs set of 3D models with specific quality that accountable to their requirement. Each user, by comparing his/her requirements with prepared quality report of 3D model, can judge about the quality of that model, modelling method and/or used input dataset for his/her work. As it is shown in Figure 30, by comparison between user's quality requirements and quality report of 3D model that prepared by assessing quality aspects and related indices, users be able to judge about 3D models, modelling method and input datasets and it would be possible for them to accept or reject 3D models, modelling method or input datasets for their works.

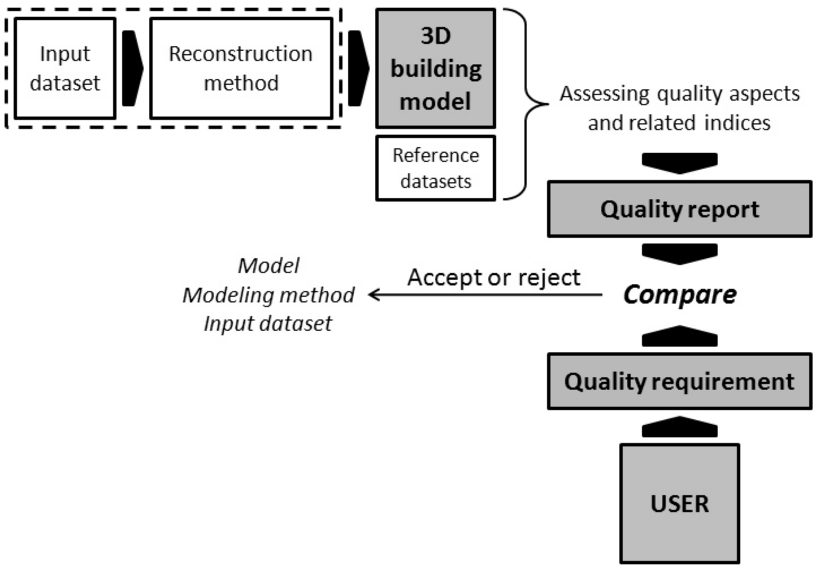


Figure 30: Shows comparison of 3D model's quality report and user quality requirements for accept or reject models, modelling method and/or input datasets.

As it mention in previous paragraphs, the introduced quality report contains descriptions about quality of 3D building model, that contains information about topology of 3D model, aspects related to roof part of 3D model (roof similarity and geometry of roof), aspects related to dormer part of 3D model (reconstruction rate, geometry of dormers) and aspects related to body part of 3D model (positional accuracy, footprint correctness and related indices, height accuracy).

2.5. Summary

In this chapter, after discuss about different methods for assessing the quality of 3D models, based on ALS as input dataset that used by different authors, various quality aspects and indices were represented. First, 'topology checks' for 3D model were introduced as one of the quality aspects. In this thesis, each 3D model, divided into three main parts and for each part related quality aspects represented. For roof part, 'roof similarity' and 'roof geometry check' were described. For dormer part, 'reconstruction rate of dormers' and 'geometry check of dormers' were described; and for body part, 'positional accuracy', 'footprint correctness' and related indices and 'height accuracy' were described.

The main idea is to prepare quality report for each 3D model by assessing each introduced quality aspect. Quality report described quality of each 3D building model individually. Preparing quality report for whole set of 3D models will be possible, by knowing quality of each 3D model (or some sample 3D models) of that set. With this quality report, users due to their requirements will be able to judge about 3D model, modelling method and input dataset for their work. If users know quality of 3D models with helps of quality report, they can accept or reject 3D models or modelling method or input dataset for their work due to their requirements.

In the following, in chapter three, reconstruction of two sets of 3D models with same input data and different modelling method will be described in detail, and in chapter four, by assessing introduced quality aspects, quality report for each 3D building model and whole sets of 3D models will be prepared. Finally, in chapter five, the results of quality reports will be discussed and checked.

3. Reconstruction methods

In previous chapter of this thesis, quality aspects that were related to 3D building models were introduced and discussed. As it described, quality aspects of 3D building models divided into four main categories: topology check, quality that related to roof part, dormer part and body part. For each parts of 3D model (roof, dormer and body) various aspects were proposed. By reconstructing some sample 3D models with different reconstruction methods, proposed quality aspects will be checked for these reconstructed models in chapter four of this thesis and also the results will be discussed.

In this chapter, first the test area and method of selecting sample buildings for reconstructing models will be described and the buildings will be chosen. Then in the second part strategy of modelling and specifications of reconstruction methods will be discussed. Also input datasets for reconstruction procedure will be introduced. After that in third section, each step of modelling method will be described and results of modelling sample models will be shown.

3.1. Building selection

3.1.1. Test area

The selected test area is a small area in north of the city named Enschede in east of the Netherlands. The reason for choosing this area as test area is because of its accessibility and different available datasets. Also this area contains more than 150 various types of buildings with different roof shapes. Moreover this area is about 5.85 hectares (0.06 square kilometres) and closure between 4 main streets. From the north to Lasondersingel St., from east to H B Blijdensteinlaan St., from the west to Lasonderstraat St. and from the south to Dr Benthemstraat St. Figure 31 shows the Enschede city and the location of test area.

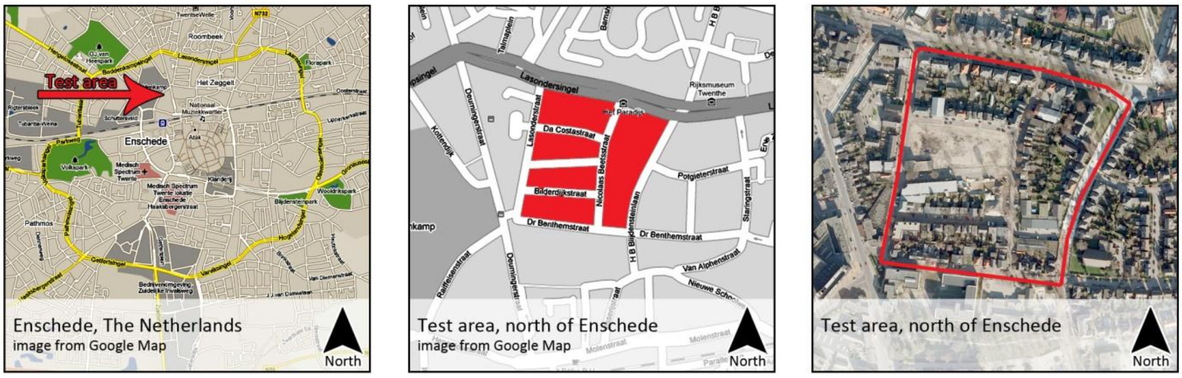


Figure 31: left map shows Enschede city and the location of test area, the centre map shows test area and the right one is the aerial image of the test area.

3.1.2. Building selection strategy

Buildings due to differences in their boundaries shape (Cheng and Gong 2008) can be classified into two classes, first class is buildings with simple rectangle footprints, and the second class is buildings with complicated footprints (footprints with more than four line segments). Buildings also have different shape of roofs (Xu et al. 2010), and due to their roofs shape it will be classified in 4 classes; flat roofs, simple 1 or 2 sloped roofs, complicated sloped roofs (roofs with more than 2 slopes) and roofs with dormers and/or extensions (Haithcoat et al. 2001). The combination of footprint classes and roof classes presents 8 types of buildings. Figure 32 shows 8 types of buildings by classifications of their footprints and their roofs.

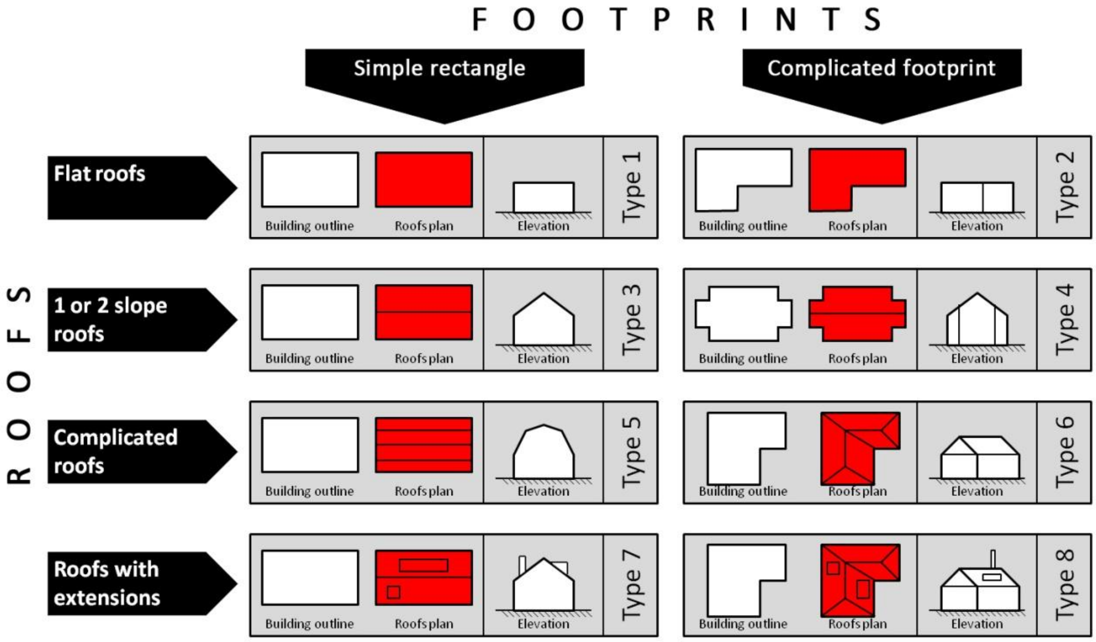


Figure 32: Shows different building footprints and roofs in 8 types.

3.1.3. Selecting buildings from test area

As it was showing in Figure 32, buildings were classified into 8 types (T1, T2, T3 ... and T8). For checking quality aspects of 3D building models, for each type, 3 buildings will be selected from test area (except T4) as sample. Therefore 22 buildings were selected from test area for reconstruction (3 buildings per type). But for T4 just one building was selected because in this area only one building with two sloped roof and complicated footprint was available. Figure 33 shows the aerial image of test area and specified 22 selected buildings.

Figure 33: Shows 22 selected buildings (3 per type, except T4) in test area with yellow circles from T1 to T8 and in the right shows their footprint with red colour.

After selecting all 22 buildings from test area in 8 different building types for reconstructing their models, buildings in each type will be listed from A to C (except type 4 that contain one building). Figure 34 shows footprint and name of each selected buildings. A, B and C were stands for number of each selected building in each type. For example three buildings were selected for building type six and they were named as T6A, T6B and T6C.

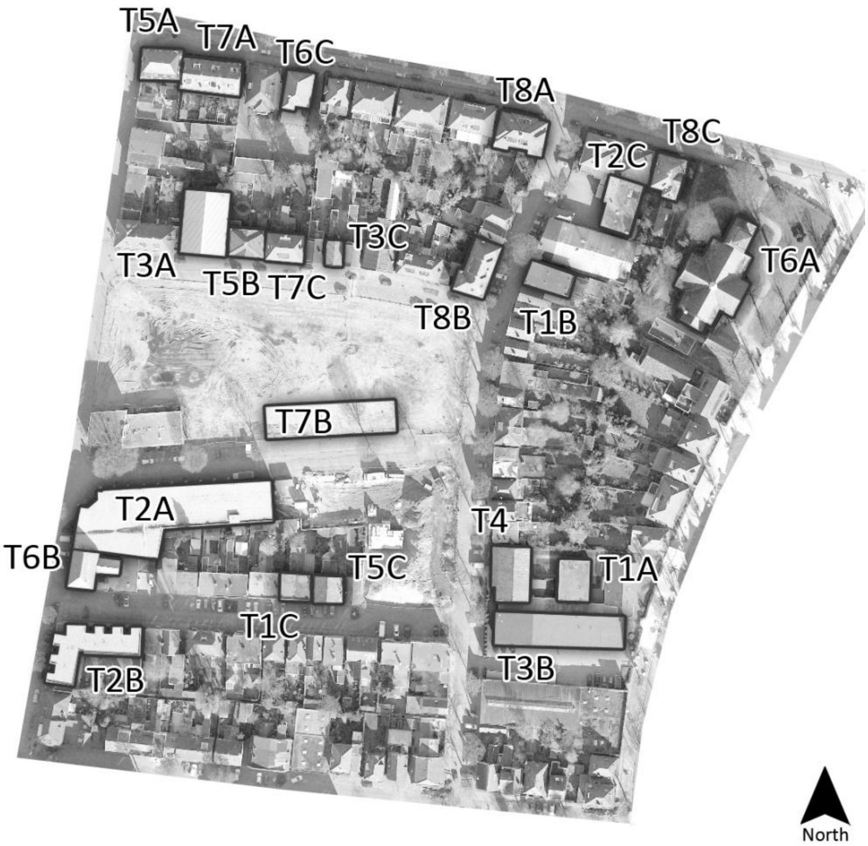


Figure 34: Shows footprint of selected buildings in red colour and their name (listed from A to C for each type except T4).

These selected 22 buildings actually are selected sample buildings from whole existed buildings in this test area. Therefore, by reconstructing model of these 22 selected buildings and assessing their quality, estimating quality of 3D building models for whole test area will be possible. These results will be discussed in 4.2.4.4.

3.2. Input datasets and modelling methods

3.2.1. Input datasets

The following datasets will be used as input dataset for reconstructing 3D models of 22 selected buildings of the test area:

Airborne Laser Scanner (ALS) dataset of the test area was acquired by FLI-MAP 400 boarded on helicopter in March 2007. The point density is about 20 points per square meter (20pts/sqm) and the height of helicopter was about 275 meter. The offsets between strips or systematic errors are 4-8 cm in X and Y coordinates and 2-3 cm in Z coordinates. The stochastic error is about 2-3 cm for X, Y and Z coordinates (Lee 2009). This dataset is geo-referenced in Dutch coordinates system. ALS will be used as one of the input dataset for reconstructing models. Figure 35 shows ALS dataset of test area.

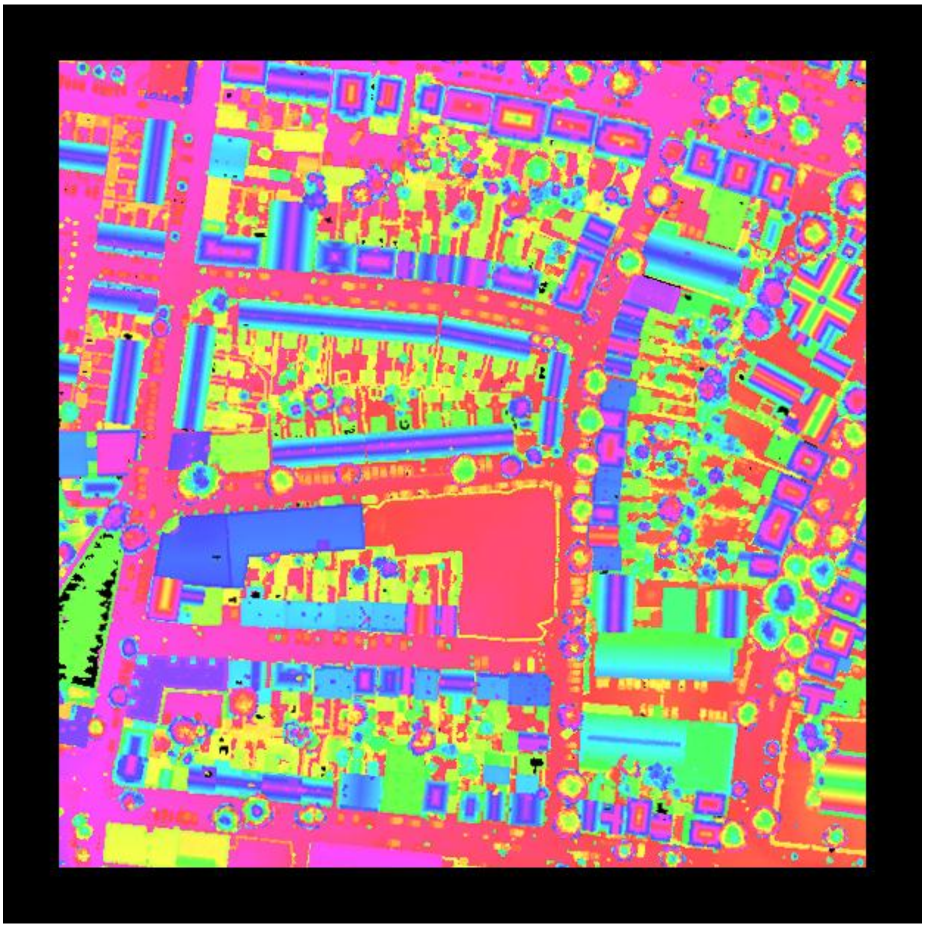


Figure 35: Shows ALS dataset of test area that was acquired in March 2007 (Screen shot from PCM software).

Cadastral 2D maps are available for this test area. In this dataset, for each building block, one closed polygon is available in vector format that represents footprints of building walls. This dataset has produced in very large scale (map scale is 1:1000). Because of the details that were mentioned on very large scale maps, this dataset is good for using as input of reconstructed 3D models with LOD-2. For assessing the accuracy of distances of this dataset, some accessible lengths were measured directly from the field. By comparing the measured lengths with their corresponding lengths from cadastral 2D maps, the RMS of distance differences turned out to be 0.15m. The available cadastral 2D maps are also geo-referenced in Dutch coordinates system. Figure 36 shows the available cadastral 2D maps of test area in one scene.

Figure 36: Shows cadastral 2D maps of test area.

3.2.2. Reconstruction methods

Meanwhile, different computer programs are available that they use ALS as input datasets for reconstructing 3D models, such as QT Modeller and MARS. In this case, Point Cloud Mapper (PCM) will be used as software for semi-automatic reconstruction. On the other hand, automatic software will be used that automatically reconstruct 3D models with ALS and cadastral 2D maps as input datasets (Oude Elberink 2010). In following each of these two automatic and semi-automatic methods and their software will be introduced:

In Semi-automatic method ALS used as input dataset and footprint of buildings will be fitted manually. For this reason, Point Cloud Mapper (PCM) will be used as a semi-automated interactive program for modelling buildings in laser scanner point clouds that authored by Vosselman. In this software laser point clouds used as input data. The strategy of reconstructing 3D models with PCM is manually editing and refining the results of each step of reconstruction if it’s necessary. In the next part, steps of reconstruction 3D models in this software will be described.

In automatic method, ALS and cadastral 2D maps were used as input dataset. The automatic method with were used for reconstructing automatic set of models in this thesis was proposed by Oude Elberink in 2010. This method reconstructs 3D building models with using available 2D maps for extracting model's footprints; and using ALS for reconstructing roof and dormer part of 3D models (Oude Elberink 2010). In next part of this chapter, the steps of reconstructing 3D models from this automatic method will be described.

3.3. Modelling strategy

In this section the reconstruction steps of each semi-automated method and automated method for modelling will be introduced and described briefly. For automated modelling method, ALS and Cadastral 2D maps will be used as input data. And for semi-automated method, the PCM software will be used and ALS data will be used as input data.

3.3.1. Semi-automatic reconstruction method

For reconstructing 3D building models with PCM software and using ALS as input dataset, the following steps has been done for this procedure:

Due to big size of the input dataset file of the test area (ALS dataset) first, each of the selected buildings with their surrounding area were visually selected with "select area on canvas" tool; after that, laser data of selected buildings were cropped with "crop laser data" tool. So the ALS input dataset would be split. By doing this procedure for all 22 buildings with their surrounding area and save each file separately, finally 22 files would be available with smaller size. Positional information of laser points of these 22 laser data files would be saved automatically by PCM software in ".laser" format.

Second step is the segmentation of the laser dataset. In this step, it is important to set segmentation parameters for further steps. In this case, after setting segmentation parameters, the storage model would be Kd-tree and surface model would be planar with surface growing radius of 1.0. By "surface growing" tool the laser dataset would be classified into different segments. Also by using "remove small segments" tool, the small segments had been removed.

Third step is to define local ground level of 3D models by selecting ground level segments such as road asphalt segment and with "determine local ground height" tool defined it as the ground level height. By defining ground level height, models would be reconstructed above this level and building height of the models will be measured from ground level height.

The fourth step of reconstructing 3D models with PCM is to create building footprints (outlines) by selecting roof segments. In PCM software, footprints of buildings would be fitted from ALS and didn't extract from other datasets like Cadastral 2D maps, so roof outlines were used as building footprints in this method. In this case the outlines first were fitted automatically by using "fit rectangular map line" tool for building footprint types 1, 3, 5 and 7 or using "fit polygonal map line" tool for building footprint types 2, 4, 6 and 8. After fitting building footprints, if it was necessary, the nodes of the outline were edited with "move point" tool visually. Finally the footprint of each building was saved in ".objpts" and ".top" format.

After fitting building outlines, the fifth step would be fitting the roof shape. In this step, first, segments that related to roof must be select with “select laser segment” tool, and then with “select map line” tool the building outline must be selected. After that due to the shape of the roof by using one of the following tools: “fit flat roof”, “fit shed roof”, “fit gable roof”, “fit hip roof”, “fit double sloped hip roof”, “fit gambrel roof”, “fit sphere roof”, “fit cone roof” or “fit cylinder roof”, the reconstructed 3D model would be shown in new window. Moreover by using “automatic reconstruction” tool instead of using different roof shapes the model would be reconstructed.

The final step is accepting 3D building model with “accept reconstructed model” tool, the reconstructed model would be accepted. By saving the output 3D model in “.objpts” and “.top” format, the reconstruction procedure were finished. By “edit reconstructed model” tool, the modeller is able to edit 3D model.

Figure 37 is showing 6 steps of reconstructing 3D models in PCM software with ALS as input dataset and Figure 38 shows the types of method (automatic/manual) in each step. As it has been mentioned before, the strategy of modelling is to manually refine and edit the results of each step if it is necessary. As it is shown in Figure 38, modeller can edit and refine the results of segmentation step by removing small segments or removing unusable segments or points, or in step 4, after automatically fitting outline map, modeller can edit the outline map manually if it is necessary. Finally in the end, after choosing roof shape and/or roof faces, modeller can edit the 3D model manually.

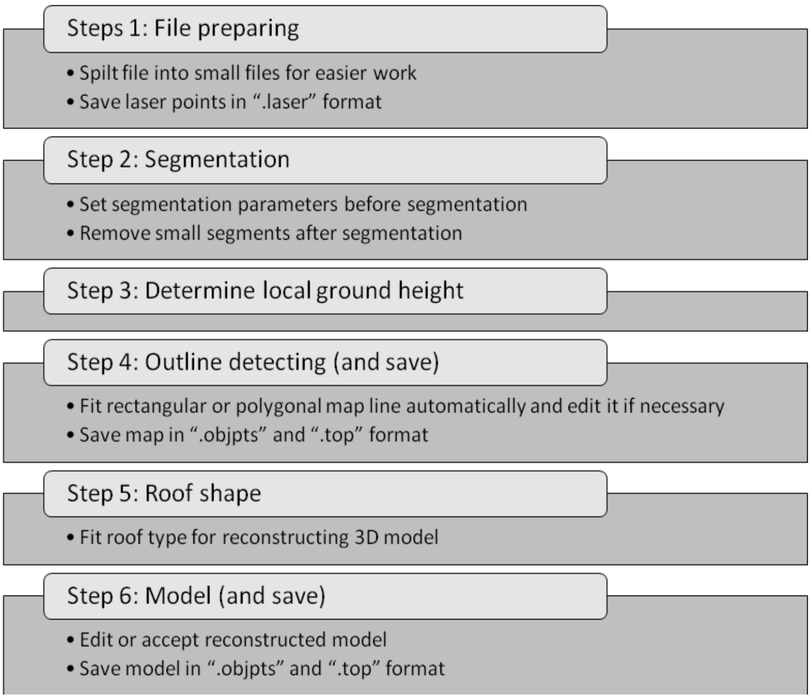


Figure 37: Shows 6 steps of reconstructing buildings from ALS input dataset with PCM software.

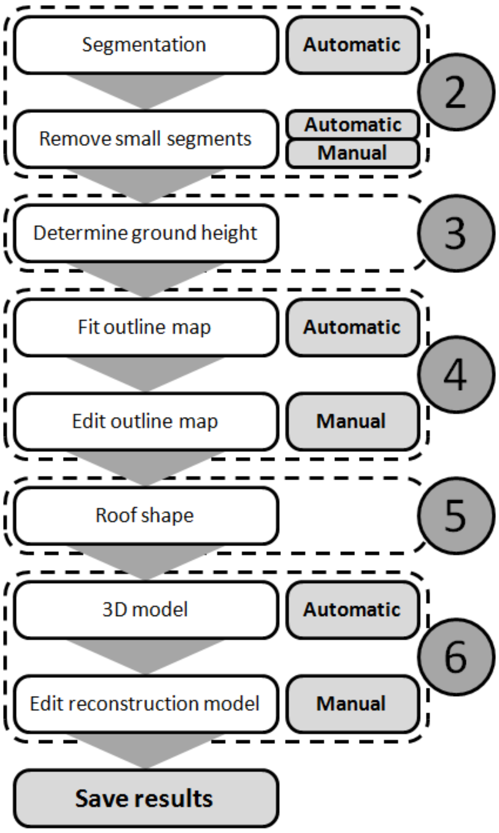


Figure 38: Shows automatic and manual steps of PCM method. Manual steps in green colour and Automatic steps in yellow. And the results will be saving as 3D model in ".objpts" and ".top" formats.

In the following, 3D modelling steps of 22 selected buildings will be described briefly. As it has been mentioned, 8 different types of buildings were defined from T1 to T8.

In semi-automatic modelling procedure, file preparation (step 1), segmentation (step 2) and determination of local ground height (step 3) has been done as it were described before; for all of the 22 models, these 3 steps had been done in the same way. For fitting building outline maps (step 4), different ways of fitting the outline maps had been used. In this thesis, fitting outline map of the buildings had been done automatically by default with "fit rectangular map line" tool or "fit polygonal map line" tool after selecting the roof segments. But for some buildings due to some errors in segmentation or due to having complicated footprints or some other problems the wrong outline was fitted and this fitted outline map was not correct; by having some manual editing, modeller try to reduce these errors and have better and realistic results for outline maps of buildings. Moreover for some buildings with complicated footprints or roof shapes, by combining simple rectangular outline maps and defining some map partition lines, or splitting buildings into simple components, reconstructed models will have better results. The following Table 2 shows type of fitting outline map for each 22 selected buildings:

Building	Footprint type	Used tool for fitting outline map
T1A	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T1B	Simple rectangular	“Fit rectangular map line” and edit manually the outline map.
T1C	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T2A	Complicated footprint	“Fit polygonal map line” and edit manually corner points with “Move point” tool.
T2B	Complicated footprint	Manually fitted the outline map by “Create new line” tool due to some noise in segmentation.
T2C	Complicated footprint	“Fit polygonal map line” and edit manually corner points with “Move point” tool.
T3A	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T3B	Simple rectangular	“Fit rectangular map line” tool and edit manually corner points with “Move point” tool.
T3C	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T4	Complicated footprint	Manually fitted the outline map by “Create new line” tool due to some noise in segmentation.
T5A	Simple rectangular	Using “Fit rectangular map line” tool, automatically and not editing for small parts of building outline and manually fitted the outline map by “Create new line” tool for building main part.
T5B	Simple rectangular	“Fit rectangular map line” and by using “Split map line” refine the results.
T5C	Simple rectangular	“Fit rectangular map line” tool and split it into 3 roof lines with “Split map line” tool.
T6A	Complicated footprint	“Fit rectangular map line” tool for each part of building and edit manually the results of each building separately.
T6B	Complicated footprint	Split building into simple components and fit outline automatically by “Fit rectangular map line” tool.
T6C	Complicated footprint	“Fit polygonal map line” tool, automatically and not editing.
T7A	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T7B	Simple rectangular	“Fit rectangular map line” tool for different components (building body and dormers), automatically and not editing.
T7C	Simple rectangular	“Fit rectangular map line” tool, automatically and not editing.
T8A	Complicated footprint	Split building into simple components and fit outline automatically by “Fit rectangular map line” tool.
T8B	Complicated footprint	“Fit rectangular map line” and by using “Split map line” refine the results.
T8C	Complicated footprint	“Fit rectangular map line” and by using “Split map line” refine the results.

Table 2: Shows the way of fitting outline maps for each 22 selected buildings.

As the above Table 2 describes, 11 building outline maps were fitted automatically with no editing, 11 building outline maps were manually fitted by modeller or by having some editing procedure results would be better. The outline map must save with “.objpts” and “.top” format.

After fitting outline map, by selecting relevant roof segments and choosing the type of roof shape from the available roof shape types or choosing “automatic reconstruction” tool for each building part separately; 3D model of that specific building part were reconstructed in a new window. In this case, if 3D reconstructed model is acceptable, 3D model would accept in PCM software. The final model must save with “.objpts” and “.top” format for future use. But if 3D model is not acceptable, by modifying it with some tools such as; “edit building model”, “reconstruct roof corner” and “reconstruct building walls”; or by applying some changes to outline map and correcting the results, the user could make it acceptable, and save it in PCM software. Table 3 is showing used roof fitting tool for reconstruction 3D model.

Building	Roof type	Used tool for fitting roof and reconstruction
T1A	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T1B	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T1C	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T2A	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T2B	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T2C	Flat roof	Using “Fit flat roof” tool after selecting segments and outline map.
T3A	1 or 2 slope roof	Using “Fit gable roof” tool after selecting segments and outline map.
T3B	1 or 2 slope roof	Using “Fit shed roof” tool after selecting segments and outline map.
T3C	1 or 2 slope roof	Using “Fit gable roof” tool after selecting segments and outline map.
T4	1 or 2 slope roof	Using “Fit gable roof” tool after selecting segments and outline map.
T5A	Complicated roofs	Using “Automatic reconstruction” tool.
T5B	Complicated roofs	Using “Automatic reconstruction” tool and “Fit gable roof” tool for building body and small building extension parts and using “Fit flat roof” for dormers.
T5C	Complicated roofs	Split roof into 3 parts and using “Fit gable roof” tool for centre part and “Fit shed roof” for side parts.
T6A	Complicated roofs	Using “Fit hip roof” tool for building tower, “Fit gable roof” tool for building body and “Fit flat roof” for dormers and extensions.
T6B	Complicated roofs	Using “Automatic reconstruction” tool for building body and using “Fit gable roof” small building parts.
T6C	Complicated roofs	Using “Automatic reconstruction” tool for building body and using “Fit flat roof” small building parts.
T7A	Roofs with extensions	Using “Fit gable roof” tool for building body and “Fit flat roof” tool for dormers.
T7B	Roofs with extensions	Using “Automatic reconstruction” tool for building body and using “Fit flat roof” for dormers.
T7C	Roofs with extensions	Using “Fit hip roof” tool for building body and using “Fit flat roof” for dormers.
T8A	Roofs with extensions	Using “Automatic reconstruction” tool for building body and small building extension parts and using “Fit flat roof” for dormers.
T8B	Roofs with extensions	Using “Automatic reconstruction” tool for building body and using “Fit flat roof” for dormers.
T8C	Roofs with extensions	Using “Automatic reconstruction” tool for building body and using “Fit flat roof” for dormers.

Table 3: Shows used roof fitting tool for reconstructing models.

As in mention before, complicated building shapes were split in simple building parts and by merging simple 3D models, whole model were reconstructed. Figure 39 shows example of one complicated building (T6A) that were split into some simple parts for reconstruction.

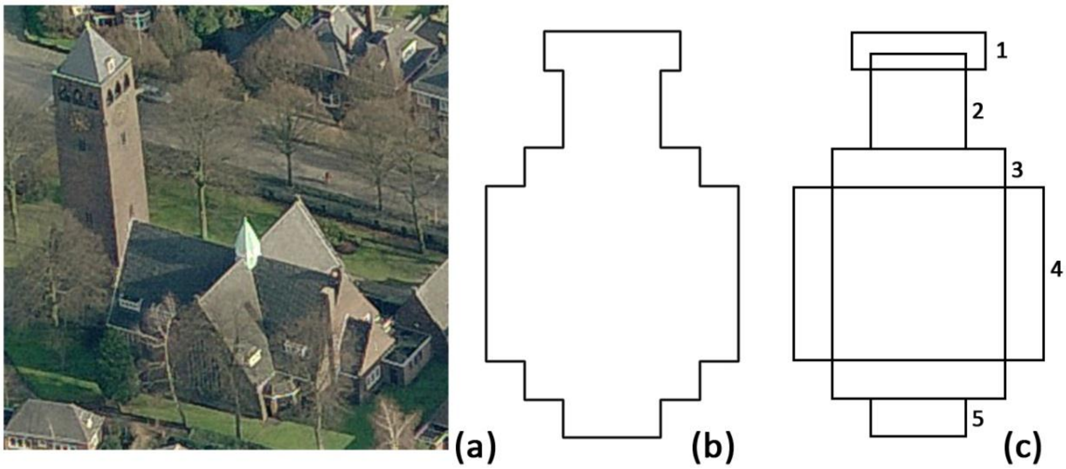


Figure 39: Shows T6A as a complicated building and split it into simple parts for reconstruction. (a) Shows the picture of church with complicated footprint as it is shown in (b). (c) Shows split footprint into 5 simple rectangular outline maps. And after reconstruction by merging simple 3D models, whole 3D model will be reconstructed in 1 block.

Figure 40 shows the results of semi-automatic reconstruction method for whole 22 models together in one 3D scene.

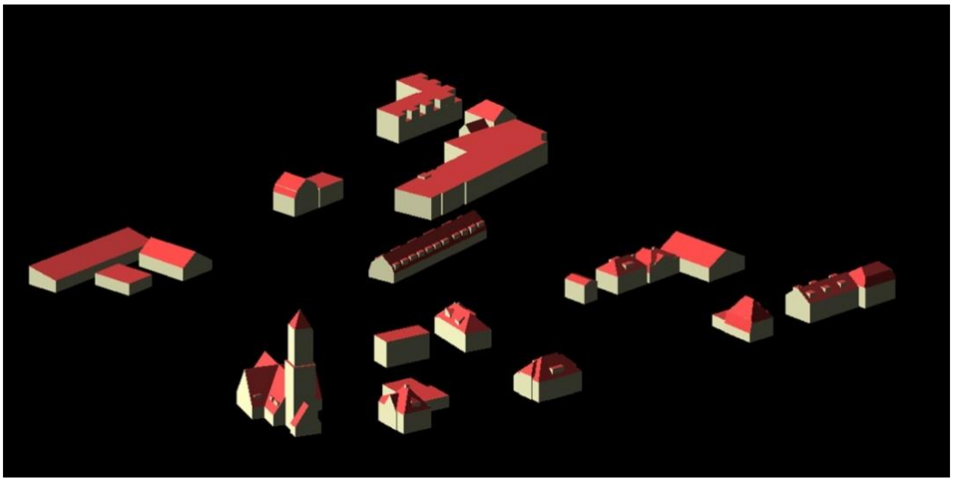


Figure 40: Shows all 22 models in one 3D scene.

3.3.2. Automatic reconstruction method

Automatic procedure that were introduced by Oude Elberink in 2010 will be used as automatic method for reconstructing 3D building models in this thesis (Oude Elberink 2010). In this method ALS dataset and cadastral 2D maps were used as input datasets. In the following paragraphs, each steps of reconstructing 3D models of this method will be described shortly and at the end the final results of reconstruction models of test area will be showed.

As it was mentioned, this automatic method was used ALS and cadastral 2D maps as input datasets for reconstructing 3D models. With helps of cadastral 2D maps, roof faces from ALS were detected. In this case, based on segments in polygon algorithm, planar segments that were partly (more than 50%) be inside the polygons of 2D maps were detected and whole segment were selected as roof segments of that polygon. As it was mentioned, cadastral 2D maps represent footprints of building walls, so by selecting whole segments of roof faces, overhangs in buildings were considered too.

Segmentation algorithm that were used in this method is based on surface growing (Vosselman et al. 2004).

Ground level height were taken from the minimum height of the laser points were locates 2 meter near the polygon for the whole set.

Location of roof faces boundaries were determined by calculating intersection lines. This method, based on height jumps and intersection lines were constructed roof topology for each selected roof segments. By comparing each edge in the roof topology graphs and different available edges in target graphs that represents different roof structures, matched corresponding edge in target graph were chosen. Roof parts of most of the buildings in reality can be described as collection of simple roof structures (Suveg and Vosselman 2004), So, used graph matching algorithm in this method, were detected structures based on comparison their topology instead of their geometry with target graph. In this method, by starting the comparison with the most complex target and stop the procedure when a complete match were found, redundancy in information wouldn't be appear (Verma et al. 2006).

Used automatic method for reconstructing 3D building models was model driven method. In this method, models were reconstructed based on targets instead of individual segments. Also in this method, walls were reconstructed based on the location of the roofs instead of boundary of cadastral 2D maps polygons.

In this automatic method, dormers were created by rectangular shapes and with horizontal roof part. Finally, walls in this method were reconstructed in first floor with polygons of cadastral 2D maps and above the first floor; walls were overlapped with roof outlines and 3D building models were reconstructed.

For reconstructing models with automatic method, segments with minimum 70 points were taken. Also, minimum length of intersection line was one meter.

The following Figure 41, shows workflow of automatic method from input datasets to 3D models (Oude Elberink 2010).

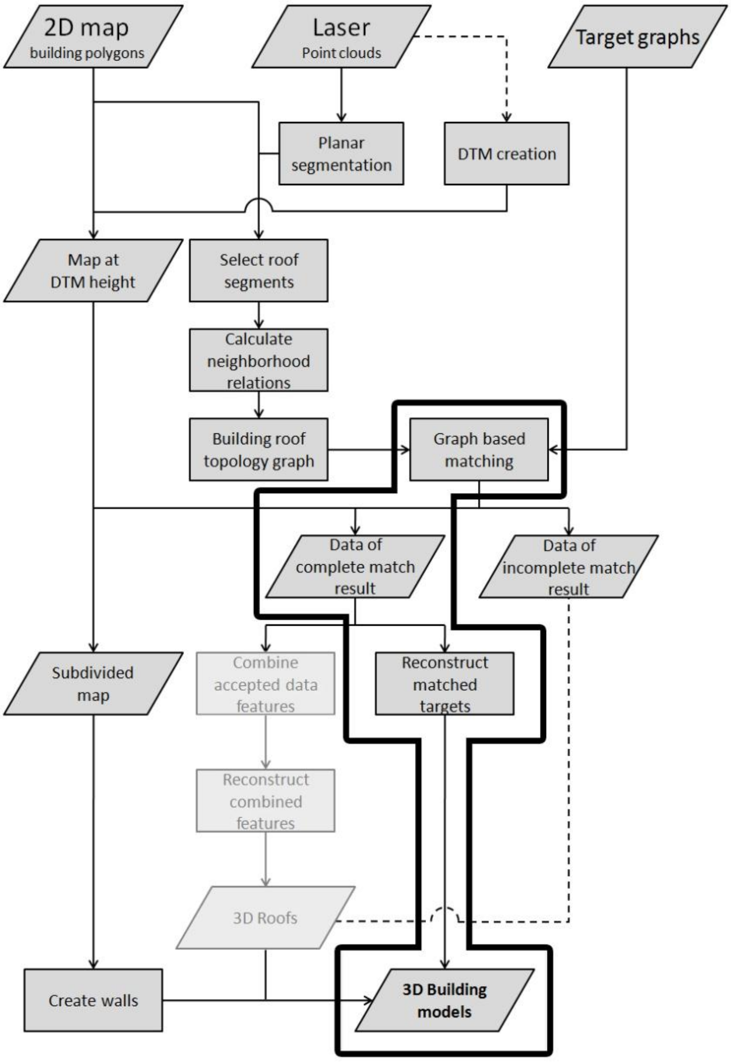


Figure 41: Shows workflow of automatic reconstruction method (Oude Elberink 2010). Bold lines mentioned used method for reconstructing 3D building models.

All of the above steps were done for reconstructing 3D models in automatic method with ALS and cadastral 2D maps as input dataset. The results of this modelling can be export in ".dxf" format for future quality checks. Figure 42, shows the results of automatic reconstruction method for whole test area in one 3D scene of PCM software.

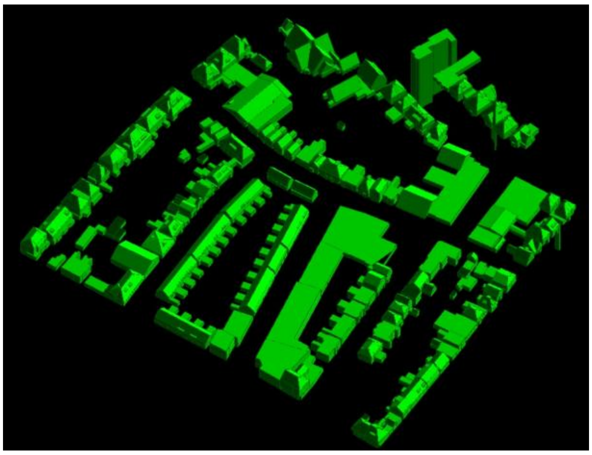


Figure 42: Shows automatic reconstructed models in one 3D scene.

4. Quality assessment

The goal of this chapter is to assess the quality aspects of each reconstructed 3D models. As it was mentioned in chapter two of this thesis, various quality aspects were introduced for assessing quality of each 3D building model individually. Introduced quality aspects were classified into four main classes: topology check, quality aspects related to roof's part, quality aspects related to dormer's part and quality aspects related to body part. Moreover, in previous chapter, with two reconstruction approach, two sets of models were reconstructed (22 sample buildings were selected and their 3D models were reconstructed in two sets of models for assessing their quality and preparing quality report).

In this chapter, first, for assessing each quality aspect, reference dataset will be selected from available datasets of test area. Then with chosen dataset as reference for each quality aspect, quality of each 3D building model will be assessed individually in both sets of models (quality of each 22 sample 3D models will be assessed in both sets). In this part, applied method for assessing each quality aspect and used software and the results will be described. And finally, quality report for each 3D model and also whole set of 22 3D building models will be prepared. Furthermore, by preparing quality report, recognizing usefulness of 3D building models and/or used reconstruction method will be possible for users due to their requirements.

4.1. Reference datasets

4.1.1. Available datasets

For selected test area in north of Enschede in east of the Netherlands Figure 31, the following datasets are available: Airborne Laser Scanner (ALS), cadastral 2D map, high resolution nadir images and oblique images. As it described in chapter three, ALS and cadastral 2D map were used as input datasets for reconstructing 3D models. As it was mentioned earlier, for automatic approach both datasets were used. For semi-automatic approach just airborne laser scanner point clouds were used as input dataset. In the following, short description of listed available datasets will be presented:

- Airborne laser scanner (ALS): described briefly in chapter three3.2.1, (Figure 35).
- Cadastral 2D map: described briefly in chapter three3.2.1, (Figure 36). It is mention that available cadastral 2D maps must be in comparable level of details in comparison to 3D models (LOD-2). So, with helps of Autodesk® AutoCAD software, small parts of footprint were removed from cadastral 2D maps. In this situation, generalized cadastral 2D map would be in same LOD-2 with reconstructed and the comparison would be possible.
- Oblique images: available oblique images are set of 10 oblique Pictometry images that were taken in February 2010. The flying height was 920 meter and tilt angle was 50 degree. The theoretic accuracy of these images are between 22cm to 44cm in X and Y axes and between 18cm and 37cm in Z axes (Gerke 2009). These images were calibrated with 29 locators in Autodesk® Image modeller software (2009a). Each locator locates at least in two images. On the other hand, for geo-referencing the calibrated images in Dutch coordinate system,

location (x, y and z) of six sample tie points of test area were measured in the field with GPS instrument. These tie points were used in Autodesk Imagemodeler software for geo-referencing calibrated images. The accuracy of geo-referenced calibrated images is 28cm in X axes, 17cm in Y axes and 10cm for height.

- High resolution nadir images: two high resolution nadir images those taken in 2008 are available. These images were captured in height of 1170m and baseline 300m. Theoretic accuracy of these images is 5cm in X and Y axes and 26cm in Z axes. These images were calibrated and geo-referenced in Dutch coordinate system as same as available oblique images that were introduced in previous paragraph with same method and using same software. The size of each high resolution nadir image is 11500x7500 pixels.

4.1.2. Reference dataset per quality aspect

As it was described in previous paragraphs, each of the above available datasets has their own characteristics and quality. For evaluating each of the proposed quality aspect, a reference dataset is needed (except topology checking that don't need reference). In the following Table 4, suitability of each available dataset for using as reference dataset for assessing each quality aspect is shown by colours. As it shows in the table, 'black colour' used when specific dataset isn't suitable for using as reference dataset, 'green colour' used when specific dataset is suitable for using as reference and 'yellow colour' used when specific dataset may be useful for using as reference but it isn't the best choice.

Quality aspects		Available datasets from test area			
		Cadastral 2D map	Nadir images	Oblique images	ALS
Roof	Roof similarity				
	Geometry of roof (height)				
Dormer	Reconstruction rate				
	Height				
	Length				
Body	Positional accuracy				
	Footprint and related indices				
	Height				

Table 4: Shows suitability of available datasets for using as reference for assessing each quality aspect. Black colour is for not suitable to use as reference dataset, green colour is for suitable to use as reference and yellow colour is for suitable to use as reference but not the best choice.

From the results of Table 4, the best reference dataset will be chosen from available datasets for assessing each quality aspect. It is important to notice, the chosen dataset is the most suitable available dataset for using as reference in comparison with the other available datasets. In the following Table 5, chosen reference datasets for assessing each quality aspect listed.

Quality aspect	Model set	Reference dataset
Roof similarity	Semi-automatic models	Oblique images
	Automatic models	
Dormer's reconstruction rate	Semi-automatic models	Oblique images
	Automatic models	
Dormer's geometry (depth and length)	Semi-automatic models	Nadir images
	Automatic models	
Positional accuracy	Semi-automatic models	Nadir images
	Automatic models	Nadir images, semi-automatic models
Footprint correctness and related indices	Semi-automatic models	Cadastral 2D map
	Automatic models	Semi-automatic model's footprints
Height accuracy (body, roof)	Semi-automatic models	Comparison of highest Z value of each building between two sets of models, ALS and oblique images.
	Automatic models	

Table 5: shows list of chosen reference for each aspect from available datasets from test area.

In the next part, assessment of each quality aspect for each individual 3D building model in both semi-automatic models and automatic models will be described briefly and the results will be compared and presented.

Evaluating quality aspects of roof's geometry will be discussed in body part 4.2.4). The quality assessment of outer roof edges and the footprint of building body and also relation between these two will be discussed in quality assessments of footprints (4.2.4.2). Total height of a building consists of two sub parts (height of roof + height of body) (Figure 54), so, the accuracy of roof heights will be assessed in the height accuracy part (4.2.4.3).

4.2. Quality assessment

After choosing the most suitable reference dataset for each quality aspect from available datasets, in this part, each quality aspect will be assessed for all of 22 3D reconstructed building models individually in both sets of models.

4.2.1. Topology

One of the quality aspects that must be check for 3D models is topology checking. As it was mentioned in chapter two, for topology check, there is no need to have reference dataset. With visual inspections in Autodesk® True viewer software and Google® Sketch-up software (free version), topology check of reconstructed 3D models will be possible. By using these two software's, rotating, zooming and orbit viewing of 3D models scene will be easily possible and checking topological characteristics of 3D models will be analyzable. As it is mentioned before, because of reconstructing models in LOD-2, interior of 3D building models and bottom face of body part are not important, so for topology check, just mention on crust surface of 3D building body is sufficient.

Topology checking has been done for all of 22 semi-automatic 3D models individually by visual inspection of 3D model's node, line and face of their body in Autodesk® True viewer software and Google® sketch-up software. Topology of 20 models in this set was correct and just two of them don't have correctness in topology because of missing faces. Tower part of T6A (Church) has missed face in roof part. Also T6C has one missed roof face. In the following, Figure 43 shows missed faces of these two 3D models that were reconstructed with semi-automatic method.

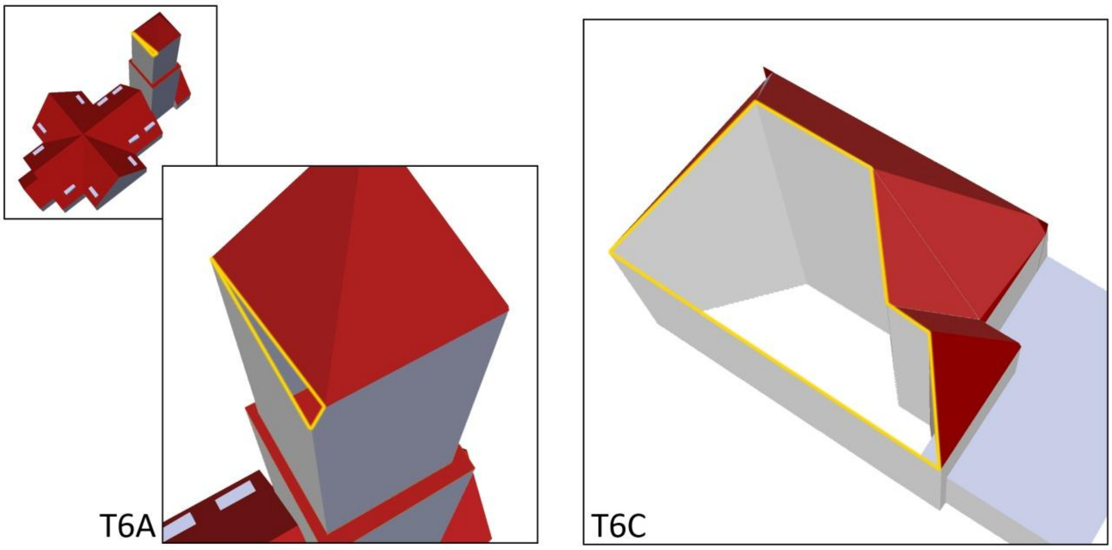


Figure 43: Shows semi-automatic 3D models with incorrect topology by showing their missed faces. Missed faces shows by yellow outlines.

For topology checking of automatically reconstructed 3D models, the following results were achieved; In adjoins of roof and body part, in the case of overhanging (bigger roof surface than body), in 7 out of 22, the bottom face of roof part were missed (T3A, T3C, T5B, T7C, T8A, T8B and T8C). In addition, in T6A (Church), topology is correct but the tower and the centre part of the church were missed and were not reconstructed. Furthermore, T2B totally missed and was not reconstructed because it was not available in cadastral 2D map. Figure 44 shows incorrect 3D models from automatic reconstruction method, by showing missed faces from bottom view of them.

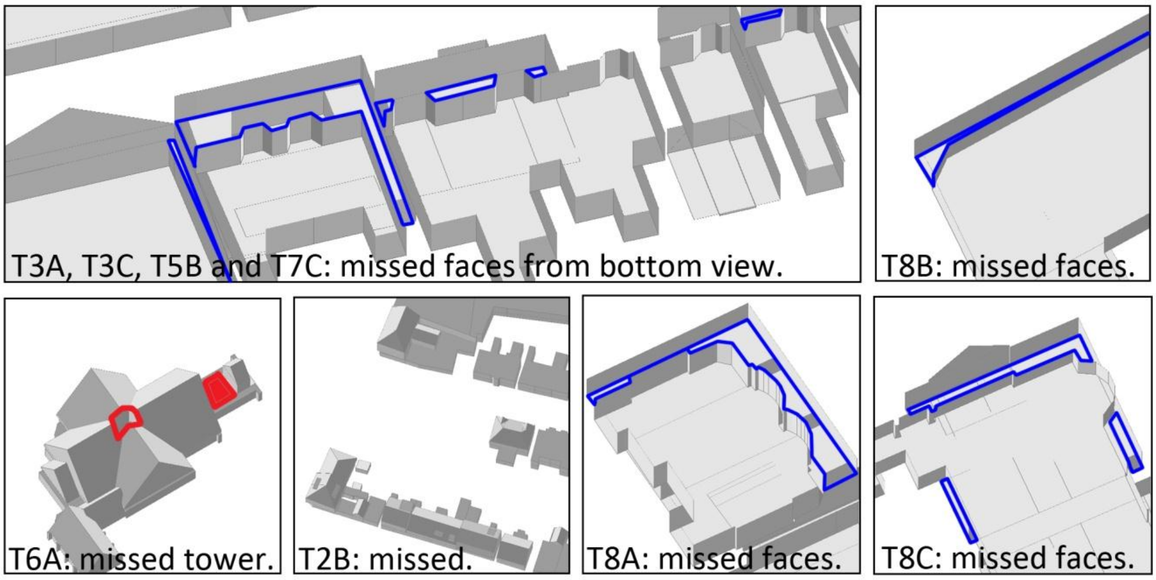


Figure 44: Shows automatic 3D models with incorrect topology by showing their missed faces from bottom view. Missed faces shows with blue outlines. And missed parts of T6A shows with red colour.

As it is mentioned in previous paragraphs, topology check for both sets of 3D models (semi-automatic set and automatic set) has been done. Comparing the results of topology check in both sets of 3D models shows that semi-automatic reconstructed 3D models usually have correctness in topology and just one roof face with complicated poly-line was missed out of 22 sample models. In this case, topology correctness in semi-automatic reconstruction method is 90.90%. In addition, automatic reconstructed 3D models have missed faces in adjoins between roof and body parts and topology correctness in automatic reconstruction method is 66.66%. Moreover, in the case of church tower (T6A), because of non vertical walls of tower part, the tower wasn't reconstructed well and one face was missed in semi-automatic model and tower part was totally missed in automatic model.

4.2.2. Roof part

As it was described in chapter two, for assessing quality of roof part of 3D models, two main quality aspects were introduced: roof similarity and geometry of roof part. Geometry checks of roof part include accuracy of roof's height and accuracy of roof's inclination. This thesis assumes that if the roof's shape were similar in both 3D model and reference, then roof's height and roof's inclination would be accurate too. This assumption is because of accuracy of heights in ALS dataset that were used as input dataset (Oude Elberink 2010). Nonetheless, height of roof part and total model's height will be discussed in height checking of body part. In this part, just similarity checking between roof of 3D model and reference will be described.

4.2.2.1. Roof similarity

Oblique images were used as reference dataset for checking roof similarity of 3D models. In this case, as it was mentioned in chapter two, first, number of roof faces in 3D model and roof faces of building in reference were compared visually. If they are equal and position and shape of each roof face of 3D model be same as its corresponding roof face in reference, 3D model has similarity in roof. But if not, there is no similarity between 3D model's roof and building's roof in reference.

Checking roof similarity has been done for 16 models with sloped roofs out of whole set of 22. In this part, church (T6A) has divided into two parts: tower and main body. So, roof similarity has been checked for 17 models.

In set of semi-automatic reconstructed models, 10 models have similarity in their roof part (T3A, T3B, T3C, T4, T6A - main body, T7A, T7B, T7C, T8A and T8C) and other 7 models haven't similarity in their roof part in comparison with reference dataset. Although T8A and T8C have small problems in ridge line, but their roofs assume as roofs with similarity in comparison with reference dataset. So, 58.80% of sloped roofs in semi-automatic set of models have roof similarity in comparison with reference dataset. Most of the 3D models that haven't got similarity in roof part are buildings with gambrel roofs (roofs with slide slope), except two models that were also mentioned on topology check because of their missed roof face (T6A - Tower and T6C). So, it can be concluded that semi-automatic method is not so good in reconstructing gambrel roofs. Figure 43 shows 3D models reconstructed with semi-automatic method that haven't got similarity in their roof part.

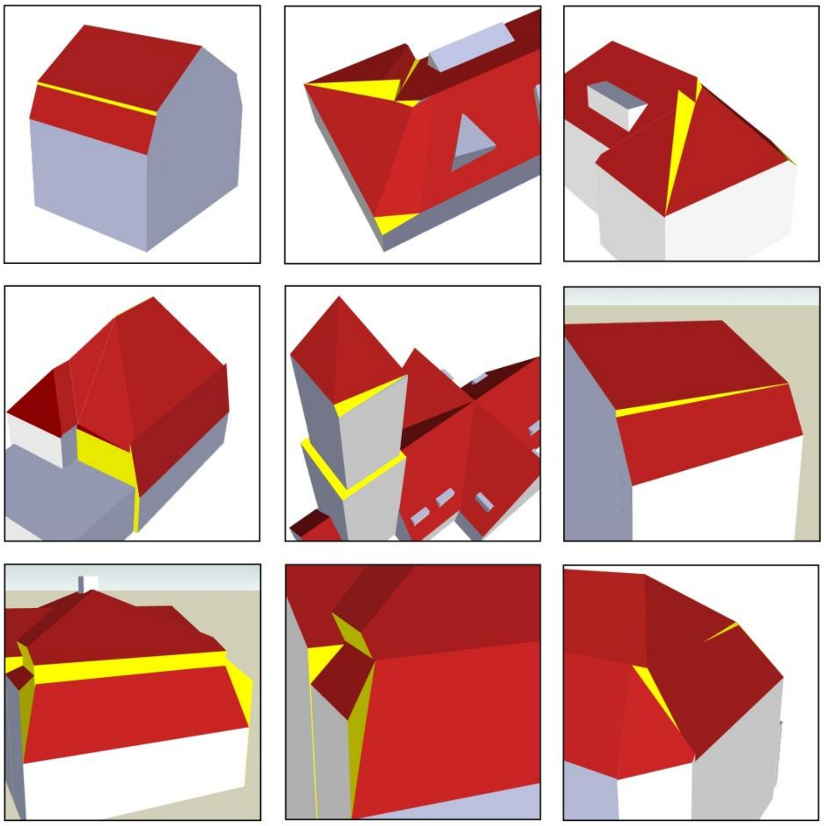


Figure 45: shows roofs with no similarity by showing incorrect roof faces in yellow colour.

In set of automatic reconstructed models, T7B in oblique images does not exist, so assessing this quality aspect for this model is not possible. But for other 15 models with sloped roofs, roof faces were compared with oblique images visually and the following results have been achieved: 7 of them had similar shape of roof in comparison with reference (T3A, T3C, T6A - main body, T7A, T7C and T8C). One of the sloped roof in reality, were reconstructed as flat roof (T3B) and the rest of the models didn't have similar shape of roof in comparison with reference (T4, T5A, T5B, T5C, T6B, T6C, T8A and T8B). So, 40.00% of 3D models in automatic set of models have roof similarity. The results shows that also models made by automatic method have some problems with reconstructing gambrel roofs (E.g. T5A and T6B) and some complicated roofs (E.g. T8A and T8B) were reconstructed incorrect. Figure 46 shows 3D models reconstructed with automatic method that haven't got similarity in their roof part in comparison with reference dataset.

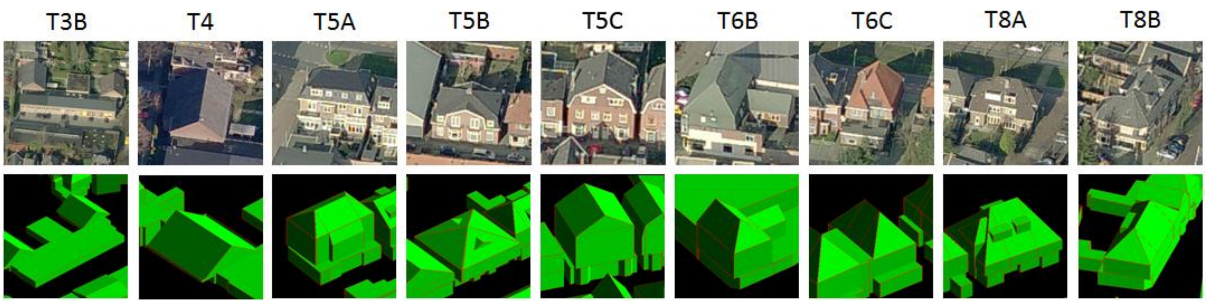


Figure 46: Shows oblique image and view of 3D models that haven't got similarity in their roof part.

4.2.2.2. Geometry of roof

Evaluating quality aspects of roof's geometry will be discussed in body part 4.2.4). The quality assessment of outer roof edges and the footprint of building body and also relation between these two will be discussed in quality assessments of footprints (4.2.4.2). The outline of roof edges and the position of corner points of roof outline will be mentioned in body part.

Total height of a building consists of two sub parts (height of roof + height of body) (Figure 54), so, the accuracy of roof heights will be assessed in the height accuracy part (4.2.4.3).

4.2.3. Dormer part

For assessing quality of dormers of 3D models, reconstruction rate and geometry checking of dormers were introduced in chapter two. 7 buildings out of 22 selected buildings in test area have got dormers; So, introduced quality aspects related to dormers will be assessed for 7 reconstructed 3D models and their dormers (T6A - main body, T7A, T7B, T7C, T8A, T8B and T8C).

For assessing reconstruction rate of dormers for each 3D model, oblique images has been used as reference dataset. By visually comparing the number of available dormers in oblique images and number of reconstructed dormers in each 3D model, assessing reconstruction rate of dormers will be possible. This comparison has been done for both semi-automatic set and automatic set of models with 45 available dormers in reference. The result of dormer's reconstruction rate has been shown in Table 6. As it is showing, 93% of available dormers were reconstructed in semi-automatic set and for automatic set, reconstruction rate of dormers is 35%. It is mentioned that for one automatic 3D model (T7B) there isn't reference. So, assessing reconstruction rate for automatic set has been done for 6 models.

Model	Available dormers in reference	Semi-automatic set		Automatic set	
		Reconstructed dormers	Reconstruction rate	Reconstructed dormers	Reconstruction rate
T6A	10	10	100%	0	0%
T7A	6	6	100%	4	66%
T7B	17	17	100%	-	-
T7C	2	2	100%	2	100%
T8A	3	3	100%	3	100%
T8B	3	3	100%	1	33%
T8C	4	1	25%	0	0%
	Total results:	42	93%	10	35%

Table 6: Shows the results of dormer's reconstruction rate in both semi-automatic set and automatic set.

The results shows that, in semi-automatic set, because of user's role in reconstruction procedure, most of the dormers were reconstructed and just 3 small dormers (dormers with area less than 2sqm) wouldn't be detected and reconstructed. In this set, the smallest reconstructed dormer has a 2sqm area and belongs to one of T6A dormers.

On the other hand, in automatic set, dormers of church's main body (T6A) were totally missed (10 dormers). The reason for not detecting dormers of church is because of defining threshold of one meter for detecting intersection lines in automatic method algorithm. It can be concluded, automatic method were detected and reconstructed big dormers (dormers with area more than 4sqm) and small dormers wouldn't be detected (same as semi-automatic method). In automatic set, the smallest reconstructed dormer has a 4.83sqm area and belongs to one of T7A dormers.

In chapter two of this thesis, dormer's height accuracy and dormer's length accuracy were introduced as geometry checking for assessing quality of dormers. Instead of dormer's height checking dormer's depth will be checked in this part. The reason of checking depth of dormers is mentioned in the following:

- For assessing dormer's height accuracy, there isn't any available accurate dataset that could be used as reference dataset.
- Because of using ALS as input dataset, it can be assumed that, the inclination of roofs would be reconstructed accurately.
- There is a simple mathematical relation between dormer's height and dormer's depth and roof's inclination, so, if the accuracy of dormer's depth assessed, it could be assumed as accuracy of dormer's height.
- High resolution nadir images could be used as reference for assessing depth and length of dormers. Meanwhile, nadir images are the most accurate available dataset with accuracy of 5cm in X and Y axes for using as reference.

In Figure 47 the dormer's height and dormer's depth is showing.

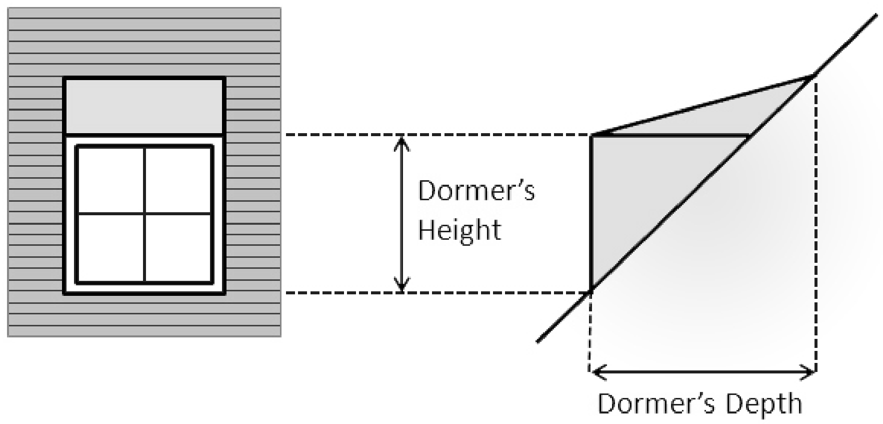


Figure 47: Shows dormer's height and depth. Because of accurate inclination and restriction in availability of accurate reference dataset, checking dormer's depth could be possible instead of checking dormer's height accuracy.

So, high resolution nadir images were used as reference for assessing depth accuracy and length accuracy of dormer part. For this purpose, depths of all reconstructed dormers were measured individually in both semi-automatic set and automatic set. These depths were measured in Autodesk® True viewer software. On the other hand, these depths should be measured from reference too. For this purpose, Autodesk® Image modeller software was used for measuring. It should be noted that for some dormers, measuring depth (or length) wouldn't be possible from reference dataset because of shadows in images. In this situation, these dormers wouldn't be used in calculating the accuracy of dormer's depth (or length). Total 20 reconstructed dormers in semi-automatic set were compared with reference, and this number is 7 for automatic set. The following Table 7 shows measured depths of each dormer from reference, semi-automatic model and automatic model; and calculate the RMS of dormer's depth for each model and for whole set of models.

Model	Dormer	Depth in reference	Semi-automatic set			Automatic set		
			Depth	ΔD	RMS	Depth	ΔD	RMS
T6A	1	0.76m	0.90m	0.14m	0.09m	-	-	-
	2	0.77m	0.86m	0.09m		-	-	
	3	0.89m	0.82m	0.07m		-	-	
	4	0.93m	0.86m	0.07m		-	-	
	5	0.92m	0.87m	0.05m		-	-	
T7A	1	2.35m	2.24m	0.11m	0.30m	2.64m	0.29m	0.15m
	2	2.47m	2.17m	0.30m		-	-	
	3	2.50m	2.25m	0.25m		2.60m	0.10m	
	4	2.24m	1.94m	0.30m		2.24m	0.00m	
	5	2.29m	1.91m	0.38m		-	-	
	6	2.61m	2.25m	0.36m		2.58m	0.03m	
T7C	1	2.09m	1.92m	0.17m	0.12m	2.30m	0.21m	0.31m
	2	1.97m	1.97m	0.02m		2.33m	0.38m	
T8A	1	1.82m	1.72m	0.10m	0.06m	2.33m	0.51m	0.66m
	2	1.90m	1.89m	0.01m		2.55m	0.65m	
	3	2.02m	2.05m	0.03m		2.81m	0.79m	
T8B	1	1.65m	1.57m	0.08m	0.39m	2.20m	0.55m	0.55m
	2	2.49m	1.91m	0.58m		-	-	
	3	2.58m	2.25m	0.33m		-	-	
T8C	1	2.14m	2.28m	0.14m	0.14m	-	-	-
				Average RMS:	0.24m		Average RMS:	0.30m

Table 7: Shows depth of each dormer in reference, semi-automatic model and automatic model and the results of dormer's depth accuracy assessment.

The result shows that, both sets of models had reconstructed dormers with nearly same RMS for depth differences between model and reference. Total RMS for depth differences between semi-automatic models and reference is 0.24cm and for automatic set it is 0.30cm.

For assessing dormer's length accuracy, same reference dataset has been chosen. With same software, lengths were measured in reference and models; and same calculations had been done and final results are showing in Table 8 for dormer's length.

Model	Dormer	Length in reference	Semi-automatic set			Automatic set		
			Length	ΔL	RMS	Length	ΔL	RMS
T6A	1	2.25m	2.60m	0.35m	0.28m	-	-	-
	2	2.50m	2.06m	0.44m		-	-	
	3	2.20m	2.50m	0.30m		-	-	
	4	2.24m	2.59m	0.35m		-	-	
	5	2.51m	2.63m	0.12m		-	-	
T7A	1	2.45m	2.47m	0.02m	0.16m	2.32m	0.13m	0.32m
	2	2.49m	2.53m	0.04m		-	-	
	3	2.40m	2.47m	0.07m		2.15m	0.25m	
	4	2.51m	2.27m	0.24m		2.16m	0.35m	
	5	2.44m	2.38m	0.06m		-	-	
	6	2.73m	2.44m	0.29m		2.27m	0.46m	
T7C	1	3.84m	3.79m	0.05m	0.06m	3.72m	0.12m	0.11m
	2	3.70m	3.77m	0.07m		3.61m	0.09m	
T8A	1	4.50m	4.59m	0.09m	0.12m	4.59m	0.09m	0.07m
	2	4.17m	4.23m	0.06m		4.13m	0.04m	
	3	2.93m	3.11m	0.18m		2.99m	0.06m	
T8B	1	5.32m	5.26m	0.06m	0.31m	5.41m	0.09m	0.09m
	2	2.83m	2.97m	0.14m		-	-	
	3	2.54m	3.05m	0.51m		-	-	
T8C	1	2.36m	3.30m	0.94m	0.94m	-	-	-
				Average RMS:	0.23m		Average RMS:	0.26m

Table 8: Shows length of each dormer in reference, semi-automatic model and automatic model and the results of dormer's length accuracy assessment.

The results of length accuracy are also shows that, both sets of models were reconstructed dormers with nearly same RMS for length differences between model and reference. Total RMS for both length and depth in both semi-automatic set and automatic set of models is between 0.23 and 0.30.

As it described, in this part, quality aspects related to dormer's part were assessed. In the next part quality aspect related to body part will be described briefly and the results will be analyzed.

4.2.4. Body part

For body part of 3D models, three quality aspects were defined. Describing used methods for assessing positional accuracy, footprint correctness and related indices and height accuracy and results of them will be described in this section.

As it is mentioned before, assessing quality of location of roof's edges (roof's outline) and position of roof's corner points will be discussed in this section.

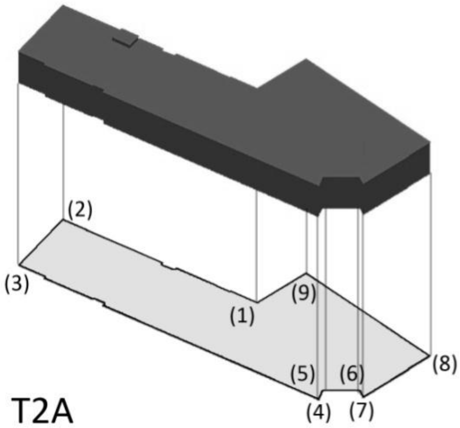
4.2.4.1. Positional accuracy

For assessing positional accuracy, RMS of X, Y and distance differences between corner points of 3D model and corresponding corner points from reference must be calculated; As it were described briefly in chapter two. By corner points of 3D model it means corner points of roof's outlines in both semi-automatic models and automatic models.

For assessing positional accuracy of semi-automatic set of 3D models, high resolution nadir images were used as reference. In this case, for all 21 models those were available in reference (just T7B wasn't available in nadir images); location of each corner point (X and Y, in same coordinate system) of each 3D model was measured with helps of Autodesk® True viewer software. The location of corresponding corner points in reference must be measured too; and these measurements had been done with Autodesk® Image modeller software. By comparing these measurements for all corner points in models and their corresponding in reference, RMS of X, Y and distance differences would be calculated for each 3D model. In addition, positional accuracy was assessed for whole set of semi-automatic models. For some buildings (E.g. church), because of shadows in some parts of nadir images, location of some corner points were missed in reference, but, in semi-automatic set, positional accuracy of each 3D model was assessed with comparing locations of at least four corner points. In the following, Table 9 lists location of each corner points of one 3D model (T2A) as sample in semi-automatic set and its corresponding corner points in reference, and differences in X value and Y value has been calculated; for each building RMS of X, Y and distance differences has been calculated. Meanwhile, Figure 48 shows position of each corner points of T2A in 3D model and corresponding in reference. This table had been prepared for all reconstructed 21 models in semi-automatic set, and the final results of RMS of X, Y and distance differences has been listed in Table 10.

T2A										
Corner point	Reference		Model		ΔX	ΔY	D	RMS X	RMS Y	RMS D
	X	Y	X	Y						
1	7838.22	1986.10	7838.29	1985.65	0.07	0.45	0.46	0.47m	0.72m	0.84m
2	7877.04	1988.68	7877.42	1988.98	0.38	0.30	0.48			
3	7876.41	2003.20	7876.32	2003.01	0.09	0.19	0.21			
4	7815.41	1998.84	7814.87	1998.99	0.54	0.15	0.56			
5	7815.62	1996.07	7815.70	1996.83	0.08	0.76	0.76			
6	7811.96	1992.29	7810.77	1993.05	1.19	0.76	1.41			
7	7809.30	1993.39	7809.22	1994.00	0.08	0.61	0.62			
8	7806.65	1978.62	7806.80	1978.56	0.15	0.06	0.16			
9	7836.48	1976.30	7836.25	1974.64	0.23	1.66	1.68			

Table 9: Shows location of corner points of one sample model (T2A) and their corresponding in reference and calculating RMS for assessing positional accuracy of this 3D model.



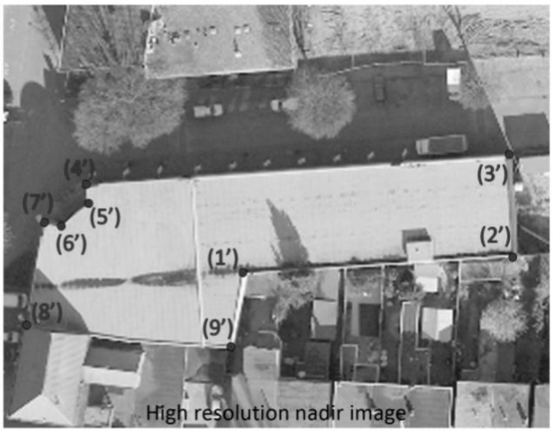


Figure 48: Shows position of each corner point in 3D model (T2A) and its corresponding in reference.

Model	RMS X	RMS Y	RMS D
T1A	0.12m	0.11m	0.16m
T1B	0.44m	0.40m	0.59m
T1C	0.43m	0.24m	0.49m
T2A	0.47m	0.72m	0.84m
T2B	0.51m	1.61m	1.12m
T2C	1.93m	0.70m	1.21m
T3A	0.30m	0.20m	0.36m
T3B	0.15m	0.45m	0.47m
T3C	0.11m	0.12m	0.17m
T4	0.17m	0.26m	0.54m
T5A	0.24m	0.20m	0.55m
T5B	0.49m	0.23m	0.54m
T5C	0.14m	0.05m	0.15m
T6A	0.39m	0.34m	0.70m
T6B	**5.21m**	**10.20m**	**11.45m**
T6C	**6.33m**	0.52m	**1.89m**
T7A	0.24m	0.11m	0.26m
T7C	0.19m	0.13m	0.23m
T8A	0.89m	0.15m	0.76m
T8B	0.72m	0.18m	0.71m
T8C	0.23m	0.11m	0.48m

Table 10: Shows the results of assessing positional accuracy of all 21 models in semi-automatic set. Bold numbers are uncommon values because of wrong position of corner point in 3D model in comparison with reference.

As Table 10 shows, for each 3D model, RMS of X differences between corner points of model and corresponding corner points in reference had been calculated. The results shows that minimum value for RMS X was calculated 0.11m, maximum value for RMS X was calculated 6.33m and average of all calculated RMS X for semi-automatic set of models would be 0.94m. As it was showed in Table 10 with red colour, there were two calculated RMS X with big uncommon values (for T6B and T6C). The reason of these two big differences in comparison with other models is because of wrong position of two corner points of these models in comparison with reference. So, if these two uncommon values (6.33m and 5.21m) had been removed for calculating average of RMS X for whole set of semi-automatic models, the result would decrease from 0.94m to 0.39m.

Results that were shown in previous paragraph for RMS X can be listed and calculated for RMS Y and RMS Distance. Table 11 shows final results of calculating RMS X, RMS Y and RMS D for semi-automatic set of 3D models.

Positional accuracy for semi-automatic set of models				
	Minimum	Maximum (uncommon)	Average for whole set	Average for whole set (without uncommon value)
RMS X	0.11m	6.33m	0.94m	0.39m
RMS Y	0.05m	10.20m	0.81m	0.32m
RMS D	0.15m	11.45m	1.13m	0.58m

Table 11: Shows final results of assessing positional accuracy by calculating RMS X, RMS Y and RMS D for semi-automatic set of models after removing uncommon values.

In addition, same procedure had been done and same software had been used for automatic models for assessing their positional accuracy. For automatic models, two datasets were used as reference: high resolution nadir images and semi-automatic set of models. By using semi-automatic set of models as reference for assessing positional accuracy of automatic models, comparison between these two set of models (and their method) will be possible.

In this case, positional accuracy was assessed for all 17 models those were available in reference out of 22. By calculating X, Y and distance differences between each corner points of 3D model and its corresponding in reference, RMS X, RMS Y and RMS D were calculated for each 3D model with helps of both reference datasets. Table 12 shows results of calculating RMS X, RMS Y and RMS D of each 17 reconstructed automatic 3D models from two reference datasets.

Models	Reference: High resolution nadir images			Reference: Semi-automatic 3D models		
	RMS X	RMS Y	RMS D	RMS X	RMS Y	RMS D
T1C	0.36m	0.32m	0.48m	0.25m	0.18m	0.31m
T2A	0.18m	0.86m	0.88m	0.46m	0.43m	0.63m
T2C	0.34m	0.59m	0.68m	1.72m	0.52m	1.80m
T3A	0.27m	0.14m	0.30m	0.15m	0.23m	0.27m
T3C	0.09m	0.13m	0.15m	0.13m	0.16m	0.21m
T4	**2.82m**	0.35m	**2.84m**	**2.85m**	0.19m	**2.86m**
T5A	0.52m	0.80m	0.95m	0.55m	0.83m	1.00m
T5B	0.79m	**2.30m**	**2.43m**	0.41m	**2.16m**	2.20m
T5C	0.84m	0.07m	0.84m	0.91m	0.10m	0.91m
T6A	1.64m	1.29m	2.09m	1.40m	1.16m	1.82m
T6B	**5.04m**	**10.36m**	**11.53m**	0.38m	0.25m	0.45m
T6C	0.26m	0.70m	0.74m	**2.15m**	0.77m	**2.29m**
T7A	0.52m	0.25m	0.58m	0.55m	0.33m	0.64m
T7C	0.18m	0.13m	0.22m	0.23m	0.24m	0.33m
T8A	0.84m	1.22m	1.48m	0.26m	1.03m	1.06m
T8B	0.75m	0.11m	0.75m	0.13m	0.25m	0.28m
T8C	0.11m	0.10m	0.15m	0.22m	0.08m	0.23m

Table 12: Shows the results of assessing positional accuracy of all 17 models in automatic set with both used reference datasets. Bold numbers are uncommon values because of wrong position of corner point in 3D model in comparison with reference.

As it were calculated in Table 12, uncommon values of X, Y and distance were showed with bold. The reason of these uncommon values is because of different shapes of roof between semi-automatic models and automatic models in comparison with reality (nadir images) and also some unclear corners of building in input dataset.

In the following Table 13, average RMS X, RMS Y and RMS D that were calculated for whole set of automatic models in comparison with helps of both used reference datasets has been shown.

Positional accuracy for automatic set of models					
	Reference	Minimum	Maximum	Whole set average	Average for whole set (without uncommon value)
RMS X	Nadir images	0.09m	5.04m	0.91m	0.51m
	Semi-automatic	0.13m	2.85m	0.75m	0.52m
RMS Y	Nadir images	0.07m	10.36m	1.16m	0.47m
	Semi-automatic	0.08m	2.16m	0.52m	0.42m
RMS D	Nadir images	0.15m	11.53m	1.59m	0.74m
	Semi-automatic	0.21m	2.86m	1.02m	0.82m

Table 13: Shows final results of assessing positional accuracy by calculating RMS X, RMS Y and RMS D for automatic set of models after removing uncommon values.

As it can be concluded from Table 13, after removing uncommon values of RMS X, Y and D, results for whole set of automatic models would be better and differences would be less in both reference datasets. In this case, average RMS X and average RMS Y of whole set of automatic 3D models would be close to 0.50m and average RMS D would be close to 0.75m from both reference datasets.

Finally it can be concluded that, buildings with not clear corners in input dataset and/or reference dataset had bigger value of RMS. In addition, in automatic set of 3D models, models with flat roofs had better results in positional accuracy when they compared with nadir images as their reference dataset rather comparing with semi-automatic models. And totally, semi-automatic models had better positional accuracy than automatic models (comparison between results of Table 11 and Table 13).

4.2.4.2. Footprint correctness

A. Semi-automatic models footprints assessment:

As it was mentioned in previous paragraphs, for assessing footprint correctness and calculating related indices for semi-automatic 3D models, cadastral 2D maps were used as reference dataset. As it were described in chapter two, 3D models were reconstructed in LOD-2, reference dataset and 3D models must have a comparable level of details. So, with helps of Autodesk® AutoCAD software, small parts of footprint were removed from reference dataset. In this situation, after generalizing cadastral 2D map, reference dataset and 3D models would be in same LOD and the comparison would be possible. In the following Figure 49, shows cadastral 2D maps of test area in red colour (a), footprints in blue colour shows footprints of selected buildings (b) and green colour shows generalized footprints of selected buildings (c).

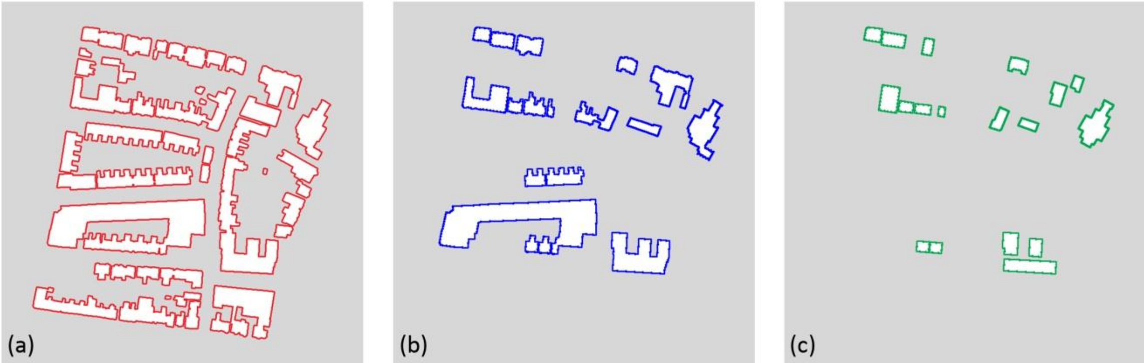


Figure 49: Shows cadastral 2D map of test area in (a), (b) is extracted footprints of selected buildings and (c) is generalized footprints of selected buildings.

Both cadastral 2D maps and ALS dataset (that were used as input for reconstructing 3D models) were geo-referenced in Dutch coordinates system; so, by importing both sets of footprints of 3D models and reference dataset in Autodesk® AutoCAD software, assessing footprint correctness and related indices will be possible. Figure 50 shows both sets of footprints in Dutch coordinate system in one scene. In Figure 50, footprints of semi-automatic 3D models are showing in black colour in (a), generalized cadastral 2D maps are showing in green colour in (b) and both datasets in Dutch coordinate system are showing in (c) in one scene.

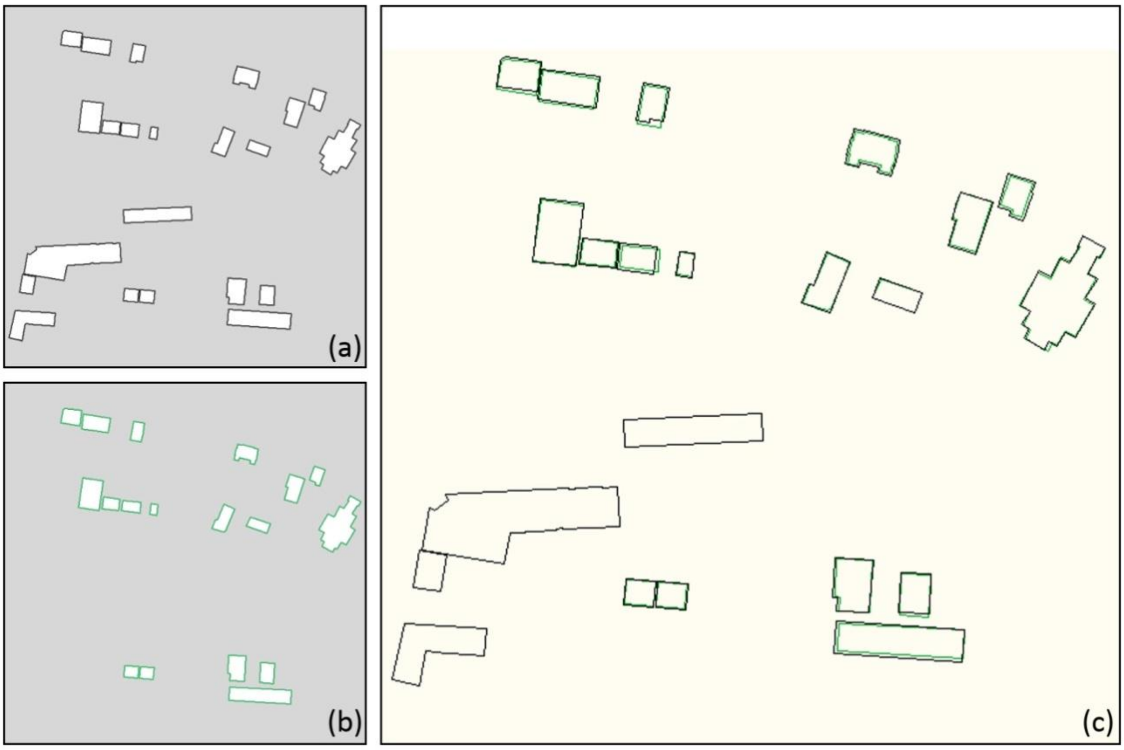


Figure 50: Shows footprint of semi-automatic 3D models in (a), (b) is generalized footprints of selected buildings of reference and (c) is both footprints of reference and 3D models in Dutch coordinate system in one scene.

As it were shown in Figure 50 (c), 18 buildings out of 22 were available in reference dataset, so footprint correctness and related indices were assessed for these 18 available footprints.

As it were described in chapter two, according to number of line segments in footprint of 3D model and reference dataset, length and angle differences between each line segment from 3D model's footprint and its corresponding line segment in reference, assessing footprints correctness would be possible for all 18 reconstructed 3D models. If number of segments be equal in both model's footprint and reference and the RMS of length differences be less than 0.50m and segments have same angle in both model and reference, then the footprint would be correct. In the following Table 14, the results of these checking is showing for each semi-automatic 3D models individually.

Model	Number of segments in model and reference	RMS length	Angle correctness	Footprint correctness
T1A	Equal	0.62m	Yes	No
T1B	Equal	0.25m	Yes	Yes
T1C	Equal	0.36m	Yes	Yes
T2C	Equal	0.60m	Yes	No
T3A	Equal	0.42m	Yes	Yes
T3B	Equal	0.85m	Yes	No
T3C	Equal	0.48m	Yes	Yes
T4	Equal	0.42m	Yes	Yes
T5A	Equal	0.72m	Yes	No
T5B	Equal	0.92m	Yes	No
T5C	Equal	0.58m	Yes	No
T6A	Equal	0.59m	Yes	No
T6C	Not equal	-	Yes	No
T7A	Equal	0.77m	Yes	No
T7C	Equal	0.60m	Yes	No
T8A	Equal	0.72m	Yes	No
T8B	Not equal	0.45m	Yes	No
T8C	Equal	>1.00m	Yes	No

Table 14: Shows footprint correctness of each semi-automatic 3D model.

Table 14 shows that the most of the semi-automatic models had equal number of line segments in comparison with their footprint in reference (about 88.88%). Also all of these 18 semi-automatic 3D models had line segments with same angle in comparison to corresponding line segments in reference. The main reason for having 13 incorrect footprints out of 18 is because of differences in segment's length between 3D models and corresponding segments in reference. In Table 14 RMS of length differences between line segments of each 3D model and corresponding line segments in reference were calculated and the average of them for whole set of semi-automatic models were 0.58m. Because of these amounts of length differences, the footprint correctness was just 27% for whole set but as it were mentioned about 88% of footprints had same number of line segments in comparison with their reference.

It can be concluded that, the main reason of length differences between line segments of 3D models and their reference is because of one of specifications of semi-automatic reconstruction method (with PCM software). In semi-automatic method, models were reconstructed by extruding roof faces of them to ground base as model's walls and this method weren't consider about roof overhangs. In this situation, the footprints of most of the 3D models were bigger than their reference and this problem will be more perceptible after calculating area based indices in next part. Figure 51 shows differences in footprint of one sample 3D model (T7C) that was reconstructed with semi-automatic method and footprint of it from cadastral 2D maps. It can be concluded that, this problem was caused because of positional accuracy and didn't considering about roof overhangs in semi-automatic method for reconstructing 3D models. In other words, footprints of semi-automatic models are same as their roof's outline.

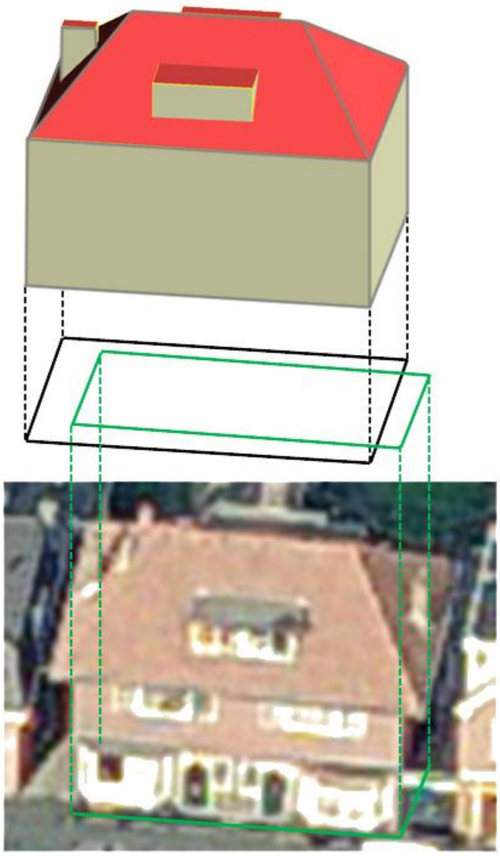


Figure 51: Shows footprint of one sample 3D model (T7C) in black colour and footprint of it from cadastral 2D map in green colour both in Dutch coordinates system and in one scene.

In addition of checking footprints correctness, some relative indices must be assessed. Two types of indices were introduced in chapter two. In this situation, also for assessing these indices, cadastral 2D maps were chosen and were used as reference dataset.

For calculating area based indices, area of model, area of building in reference, overlap area between model and reference, none extracted area of reference and incorrect area of model were measured with helps of Autodesk® AutoCAD software by importing footprints of 3D models and generalized cadastral 2D maps in one scene. With these measurements, calculating matched overlap index, area omission error index and area commission error index will be possible for all 18 models individually. Table 15 shows the results of calculating area based indices of semi-automatic 3D models.

Model	Area of reference	Model's area	Overlap area	Non-extracted Area	Incorrect area	Matched overlay	Area omission error	Area commission error
	sqm	sqm	sqm	sqm	sqm			
T1A	155.09	156.58	144.48	10.58	12.09	93.16%	6.82%	7.72%
T1B	119.78	120.91	118.74	1.20	2.00	99.13%	0.01%	0.02%
T1C	91.91	98.88	91.91	0.00	6.97	100%	0%	0.07%
T2C	206.11	223.59	206.11	0.00	17.48	100%	0%	0.08%
T3A	341.74	355.02	338.55	3.18	14.05	99.07%	0.93%	3.96%
T3B	466.98	520.36	462.51	4.46	57.85	99.04%	0.01%	0.11%
T3C	43.03	49.12	43.03	0.00	6.90	100%	0%	0.14%
T4	228.00	249.47	227.90	0.09	21.90	99.96%	0.04%	8.78%
T5A	159.50	157.80	141.11	18.38	16.69	88.47%	0.12%	0.11%
T5B	107.94	127.74	107.94	0.00	19.20	100%	0%	0.15%
T5C	91.13	102.54	91.13	0.00	11.41	100%	0%	11.13%
T6A	635.00	647.12	624.07	8.33	22.50	98.28%	0.01%	0.03%
T6C	120.18	125.38	107.21	12.96	18.17	89.21%	10.78%	14.49%
T7A	219.36	234.20	206.47	12.80	27.72	94.12%	0.06%	0.12%
T7C	109.43	128.41	99.13	10.30	29.28	90.59%	9.41%	22.80%
T8A	175.02	216.81	175.02	0.00	40.02	100%	0%	0.18%
T8B	178.99	197.43	178.56	0.42	28.82	99.76%	0%	0.15%
T8C	98.87	140.88	98.87	0.00	42.01	100%	0%	29.82%

Table 15: Shows results of calculating area based indices of semi-automatic models.

From Table 15 the average of area based indices can be calculated. For whole set of semi-automatic models the average of matched overlay would be 97.27%, the average of area omission error would be 1.57% and the average of area commission error would be 5.55%. The results prove previous statements about differences between footprints of semi-automatic models and footprints from their reference. It can be concluded that footprints of semi-automatic models are same as their roof's outline and footprint of most of the 3D models were bigger than their reference because in semi-automatic method there were not any consideration about roof overhangs.

Moreover, by measuring area and perimeter of semi-automatic models and area and perimeter from their reference, calculating shape similarity indices will be possible. In the following, results of calculating area difference index and perimeter difference index for all 18 semi-automatic models will be shown in Table 16.

Model	Area of reference	Perimeter of reference	Model's area	Model's perimeter	Area difference	Perimeter difference
	sqm	m	sqm	meter	sqm	meter
T1A	155.09	50.62	156.58	50.47	0.96	0.30
T1B	119.78	46.90	120.91	47.27	0.01	0.01
T1C	91.91	38.47	98.88	39.91	0.08	0.04
T2C	206.11	61.22	223.59	63.41	0.08	0.04
T3A	341.74	75.21	355.02	76.58	3.89	1.82
T3B	466.98	111.20	520.36	114.46	0.11	0.03
T3C	43.03	26.83	49.12	28.69	0.14	0.07
T4	228.00	62.62	249.47	65.09	9.42	3.94
T5A	159.50	50.18	157.80	50.22	0.01	0.00
T5B	107.94	42.13	127.74	45.78	0.18	0.09
T5C	91.13	38.30	102.54	40.62	12.52	6.06
T6A	635.00	134.99	647.12	133.98	0.02	0.01
T6C	120.18	46.10	125.38	125.38	4.33	**171.97**
T7A	219.36	61.95	234.20	64.48	0.07	0.04
T7C	109.43	43.34	128.41	45.86	17.34	5.81
T8A	175.02	60.92	216.81	66.45	0.24	0.09
T8B	178.99	58.24	197.43	61.87	0.10	0.06
T8C	98.87	42.38	140.88	50.01	**42.49**	18.00

Table 16: Shows results of calculating shape similarity indices of semi-automatic models. Bold numbers shows uncommon values.

For whole set of semi-automatic models average of area differences and perimeter differences can be calculated. For whole set of semi-automatic models the average of area differences would be 5.11sqm and if the uncommon big amount value (42.49sqm) were removed, the results would be decrease from 5.11sqm to 1.31sqm. For whole set of semi-automatic models the average of perimeter differences would be 11.54m and if the uncommon big amount value (171.97m) were removed, the results would be decrease from 11.54m to 1.21m. From the results of Table 16, it can be also concluded that, the most amount of area differences and perimeter differences caused because of didn't considering about roof overhangs in semi-automatic reconstruction method.

B. Automatic models footprint assessment (outline of roofs):

In previous part, footprints of semi-automatic models were assessed. As it were described, footprint assessment of semi-automatic models had been done by using cadastral 2D maps as their reference dataset; and as it were observed the main differences between footprints of semi-automatic models and their corresponding footprints from reference caused due to the used method of reconstruction of those 3D models. Also it was mentioned in that method there were no considering about roofs overhangs. So, footprints of semi-automatic models indeed same as their roof outlines.

On the other hand, in automatic reconstructed 3D models, footprints of body parts were same as cadastral 2D maps. In this situation, choosing cadastral 2D maps for assessing footprints of automatic set of 3D models wouldn't be useful. So, for footprint assessment, instead of comparing footprints of automatic models with cadastral 2D maps, roof outlines of automatic models would be compared with corresponding footprints of semi-automatic models. In other words, roof outlines of semi-automatic models would be used as reference for assessing roof outlines of automatic models. It is mention that roof outlines of 3D models with flat roofs (T1B, T1C, T2A and T2C) are same as their cadastral 2D maps. Figure 52 shows footprint and roof outlines of one sample 3D model (T4) that was reconstructed with automatic method and also shows corresponding footprint of that model in semi-automatic set that was used as reference.

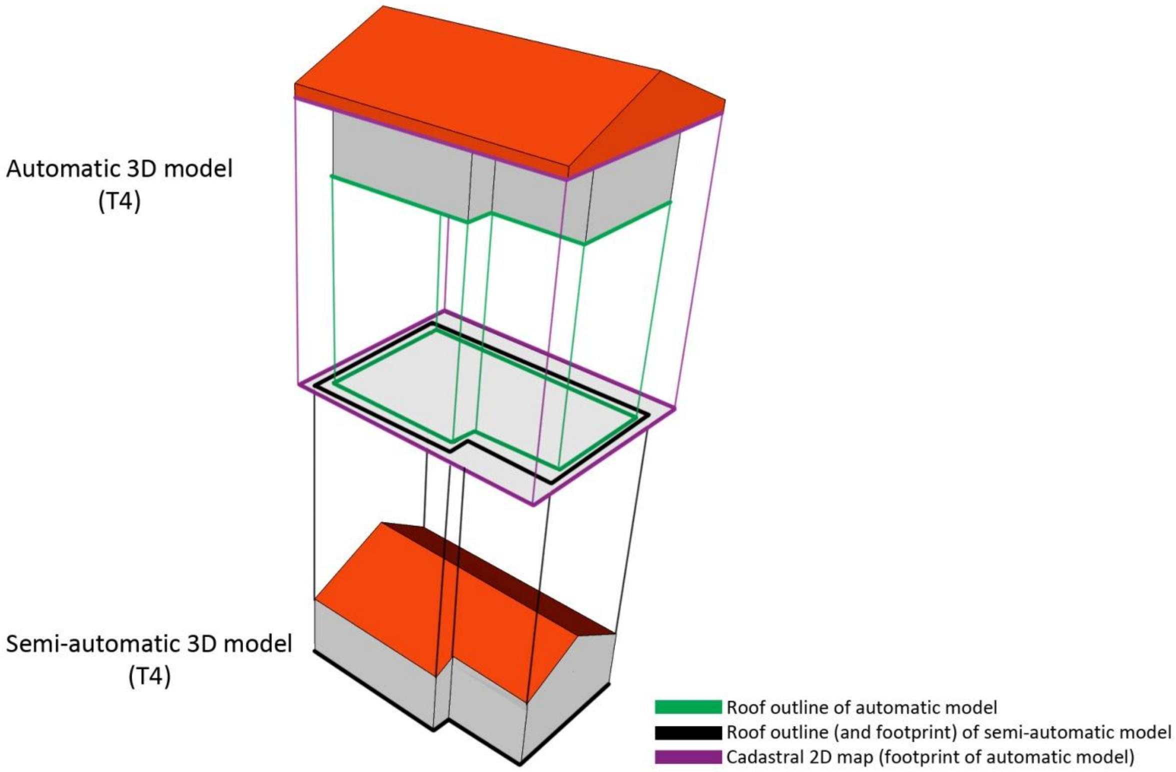


Figure 52: Shows sample reconstructed 3D model (T4) and roof outlines.

The following Figure 53 shows roof outlines of automatic models in purple colour and their reference (semi-automatic models) in black colour, both were geo-referenced in Dutch coordinates system and be in one scene. As it is showing, three models were not reconstructed in this set (T1A, T2B and T3B) and for T7B there was not comparable available reference in semi-automatic models. So, footprints of 18 models out of 22 must be assessed.

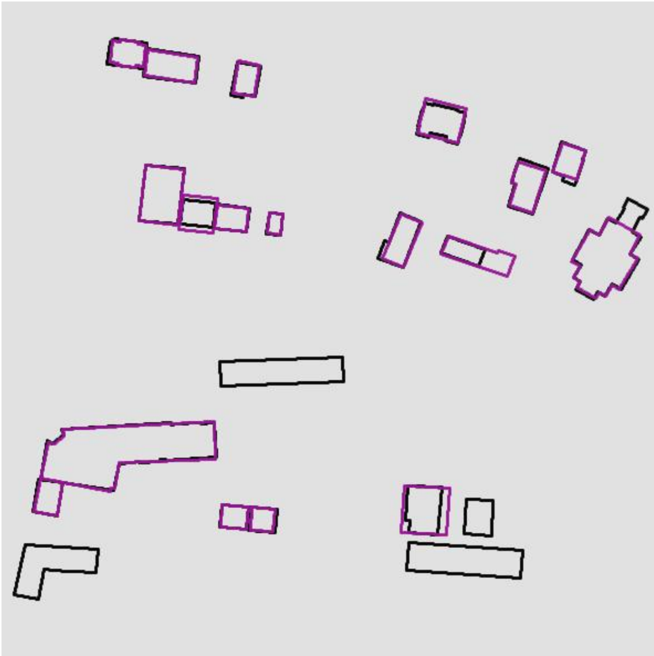


Figure 53: Shows roof outlines (footprints) of automatic 3D models in purple colour and their reference in black colour both in Dutch coordinate system in one scene.

With same method as semi-automatic models, footprint correctness of automatic models was assessed for each model individually and the result of this assessment is showing in Table 17.

Model	Number of segments in model and reference	RMS length	Angle correctness	Footprint (roof outline) correctness
T1B	Not equal	-	Yes	No
T1C	Equal	0.37m	Yes	Yes
T2A	Equal	-	Yes	No
T2C	Equal	1.00m	Yes	No
T3A	Equal	0.13m	Yes	Yes
T3C	Equal	0.28m	Yes	Yes
T4	Not equal	-	Yes	No
T5A	Not equal	-	Yes	No
T5B	Equal	3.09m	Yes	No
T5C	Equal	1.28m	Yes	No
T6A	Not equal	-	Yes	No
T6B	Equal	0.41m	Yes	Yes
T6C	Not equal	-	Yes	No
T7A	Equal	0.90m	Yes	No
T7C	Equal	0.51m	Yes	No
T8A	Not equal	-	Yes	No
T8B	Not equal	-	Yes	No
T8C	Not equal	-	Yes	No

Table 17: Shows footprint correctness of each automatic 3D model.

Table 17 shows that near half of the automatic models had equal number of line segments in comparison with their reference (about 55.55%). Also all of these 18 automatic 3D models had line segments with same angle in comparison to corresponding line segments in reference. The main reason for having 8 not equal roof outlines segments out of 18 is because of reconstruction method of automatic models for reconstructing roof parts. In Table 17, RMS of length differences between roof outline segments of each 3D model and corresponding roof outline segments in reference was calculated. This calculation was done for all models with equal roof outline segments in comparison with their reference and the average of them for whole set of automatic models were 0.89m. Because of these amounts of length differences and not equal roof outline segments, the footprint correctness was just 22.22% for whole set, but as it were mentioned about 55.55% of footprints had same number of roof outline segments in comparison with their reference. From the results of footprint correctness of automatic models it can be concluded that approximately all of the automatic models with complex footprint shapes and sloped roofs (T4, T6 and T8) had incorrect roof outlines in comparison with semi-automatic models. The reason of these differences is because of used method for reconstructing roof parts of automatic models. Also one reason for having incorrect footprints is because of a local jump of density of ALS (Cheng and Gong 2008).

In addition of checking footprints correctness, some relative indices must be assessed as same as semi-automatic models and with same methods and same calculations. Two types of indices were introduced in chapter two. In this situation, also for assessing these indices, footprints (roof outlines) of semi-automatic models were chosen and were used as reference dataset.

For calculating area based indices (matched overlay, area omission error, and area commission error) and shape similarity indices (area difference and perimeter difference) for automatic models, same assessment method that was used for semi-automatic models has been used. In Table 18 and Table 19 the results of assessing these indices are showing.

Model	Area of reference	Model's area	Overlap area	Non-extracted Area	Incorrect area	Matched overlay	Area omission error	Area commission error
	sqm	sqm	sqm	sqm	sqm			
T1B	120.91	219.27	118.74	1.97	100.53	98.21%	1.63%	45.85%
T1C	98.88	91.44	91.44	7.44	0.00	92.48%	7.52%	0%
T2A	1231.28	1226.75	1206.89	20.77	19.72	98.02%	1.69%	1.61%
T2C	223.59	193.40	193.40	30.18	0.00	86.50%	13.50%	0%
T3A	355.02	358.13	351.51	3.42	6.04	99.01%	0.96%	1.69%
T3C	49.12	45.31	45.31	3.81	0.00	92.24%	7.76%	0%
T4	249.47	340.59	246.45	2.00	94.22	98.795	0.80%	27.66%
T5A	157.80	132.97	132.97	24.83	0.00	84.26%	15.74%	0%
T5B	194.70	127.74	127.74	0.00	66.96	65.61%	0%	52.42%
T5C	102.54	83.91	83.91	0.00	18.63	81.83%	0%	22.20%
T6A	647.12	553.96	542.97	102.43	10.98	83.91%	15.83%	1.98%
T6B	132.87	127.70	124.74	8.12	2.95	93.88%	6.11%	2.31%
T6C	125.38	112.22	107.76	17.62	4.46	85.95%	14.05%	3.97%
T7A	234.20	209.04	209.04	25.16	0.00	89.26%	10.74%	0%
T7C	128.41	118.29	118.29	10.12	0.00	92.12%	7.88%	0%
T8A	216.81	238.22	206.14	10.66	32.07	95.08%	4.92%	13.46%
T8B	197.43	179.62	178.21	19.21	1.39	90.26%	9.73%	0.77%
T8C	140.88	123.67	123.67	17.20	0.00	87.78%	12.21%	0%

Table 18: Shows results of calculating area based indices of automatic models.

Model	Area of reference	Perimeter of reference	Model's area	Model's perimeter	Area difference	Perimeter difference
	sqm	m	sqm	meter	sqm	meter
T1B	120.91	47.27	219.27	73.53	**81.35**	**55.55**
T1C	98.88	39.91	91.44	38.38	7.52	3.83
T2A	1231.28	207.51	1226.75	181.68	0.37	12.45
T2C	223.59	63.41	193.40	59.12	13.50	6.77
T3A	355.02	76.58	358.13	76.83	0.88	0.33
T3C	49.12	28.69	45.31	27.57	7.76	3.90
T4	249.47	65.09	340.59	73.83	**36.53**	13.43
T5A	157.80	50.22	132.97	48.65	15.74	3.13
T5B	194.70	55.81	127.74	45.78	**34.39**	17.97
T5C	102.54	40.62	83.91	36.64	18.17	9.80
T6A	647.12	133.98	553.96	106.91	14.40	**20.20**
T6B	132.87	46.68	127.70	46.01	3.89	1.44
T6C	125.38	46.71	112.22	43.20	10.50	7.51
T7A	234.20	64.48	209.04	60.97	10.74	5.44
T7C	128.41	45.86	118.29	44.05	7.88	3.95
T8A	216.81	66.45	238.22	62.11	9.88	6.53
T8B	197.43	61.87	179.62	57.30	9.02	7.39
T8C	140.88	50.01	123.67	44.80	12.22	10.42

Table 19: Shows results of calculating shape similarity indices of automatic models. Bold numbers shows uncommon values.

From Table 18 the average of area based indices can be calculated. For whole set of automatic models the average of matched overlay would be 89.73%, the average of area omission error would be 7.28% and the average of area commission error would be 9.61%. From Table 19 average of shape similarity indices can be calculated for whole set of automatic models. For whole set of automatic models the average of area differences would be 16.37sqm and if the uncommon big amount values (81.35sqm, 36.53sqm and 34.39 sqm) were removed, the results would be decrease from 16.37sqm to 12.43sqm. It is important to note the reason of having these uncommon big amount values is because of reconstructing roof part of 3D models with simple predefined roof shapes in automatic reconstruction method. For whole set of automatic models the average of perimeter differences would be 10.56m and if the uncommon big amount values (55.55m and 20.20m) were removed, the results would be decrease from 12.43m to 7.14m. From the results of Table 19, it can be also concluded that, the most amount of area differences and perimeter differences caused because of reconstruction of roof parts with simple roof outlines and generalized shapes.

4.2.4.3. Height accuracy

For assessing height accuracy of each 3D model in set of semi-automatic and automatic models, two different measurements had been done. In the following, used procedure for assessing height accuracy of semi-automatic and automatic models will be described:

As it was mentioned in chapter three, high accurate ALS were used as input dataset for both semi-automatic and automatic method. So, for having comparison between height accuracy of semi-automatic and automatic models, height of body part, height of roof part and total height of each same 3D model had been compared in both sets of models. In this case, heights of 20 models out of 22 were measured (T2B was not reconstructed in automatic set of models and T7B was not same in two sets of model). These measurements had been done with helps of Autodesk® AutoCAD software. In the following Table 20, the results of measuring heights of body part and roof part and total height of each 3D model is showing.

Model	Semi-automatic			Automatic		
	H1, Roof	H2, Body	H total	H1, Roof	H2, Body	H total
T1A	-	3.99m	3.99m	-	2.85m	2.85m
T1B	-	8.68m	8.68m	-	6.43m	6.43m
T1C	-	6.48m	6.48m	-	5.86m	5.86m
T2A	-	7.45m	7.45m	-	7.65m	7.65m
T2B	-	9.01m	9.01m	-	-	-
T2C	-	3.91m	3.91m	-	3.62m	3.62m
T3A	4.41m	4.47m	8.88m	4.31m	4.48m	8.79m
T3B	**1.96m**	**4.10m**	**6.06m**	**0.00m**	**2.85m**	**2.85m**
T3C	1.08m	6.24m	7.32m	1.03m	6.20m	7.23m
T4	5.11m	3.11m	8.22m	5.94m	2.83m	8.77m
T5A	5.01m	6.62m	11.63m	4.93m	6.60m	11.53m
T5B	**5.73m**	**2.77m**	8.50m	**2.99m**	**5.57m**	8.56m
T5C	5.08m	6.21m	11.29m	2.79m	8.43m	11.22m
T6A	10.61m	3.78m	14.39m	10.61m	3.57m	14.18m
T6B	4.30m	8.87m	13.17m	3.98m	8.98m	12.96m
T6C	**9.17m**	**3.07m**	12.24m	**5.60m**	**6.43m**	12.03m
T7A	3.64m	6.62m	10.26m	3.49m	6.63m	10.12m
T7B	5.62m	2.81m	8.43m	-	-	-
T7C	3.64m	5.94m	9.58m	3.35m	6.42m	9.77m
T8A	7.54m	4.91m	12.45m	7.25m	4.96m	12.21m
T8B	5.75m	5.29m	11.04m	4.71m	6.14m	10.85m
T8C	6.69m	6.38m	13.07m	6.35m	6.64m	12.99m

Table 20: Shows heights of body part and roof part of each 3D model in both sets of models, bold numbers are heights with uncommon values.

From Table 20, calculating RMS of height differences between body parts of two sets of 3D models is possible. In this case, RMS H-body would be 1.30m. These calculations also had been done for RMS

H-roof and RMS H-total. The result of RMS H-roof was 1.45m and the result of RMS H-total was 0.94m.

In this comparison, three models (T3B, T5B and T6C) had big differences in their heights. In T3B, the reason of these differences is because of incorrect reconstruction of T3B that was reconstructed wrongly with flat roof in automatic model instead of one sloped roof. But in T5B and T6C, as it is showing in Table 20 with red colour, the total height of 3D model were near equal in both sets of models, but the differences caused due to measuring roof heights and body heights of these models in two sets of models. Figure 54 shows T5B that were reconstructed in both semi-automatic and automatic sets of models. As it is showing, the total height in both of these models was near equal and main differences are caused in measuring heights of roof part and body part.

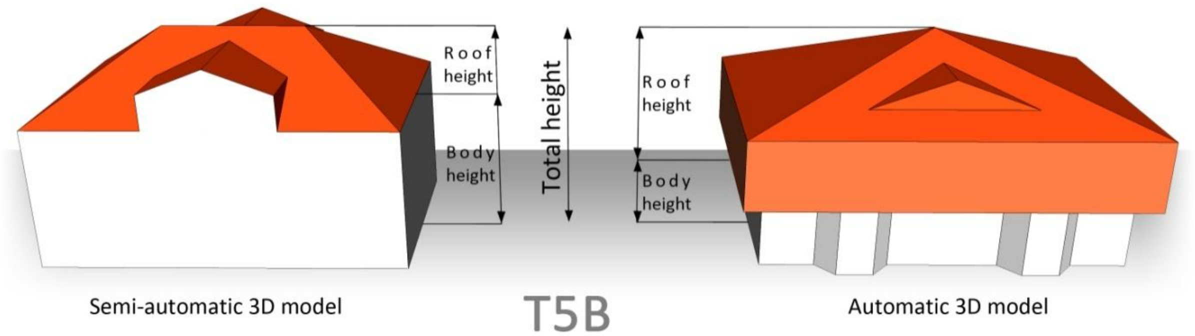


Figure 54: Shows roof height, body height and total height of T5B in both sets of models.

If the big uncommon differences were removed, the results would be decrease. In this situation, RMS H-body would be decrease from 1.30m to 1.08m, RMS H-roof would be decrease from 1.45m to 1.16m and RMS H-total would be decrease from 0.94m to 0.37m. The reason of 0.37m for RMS of H-total is because of differences in choosing ground level for measuring total heights of models in semi-automatic models and automatic models and also systematic errors in reconstruction methods. With this comparison it can be concluded that if the ground level of models were defined correctly in both sets of models, total height of models in both sets of models would be near same.

On the other hand, for assessing height accuracy of 3D models, highest elevation point (Z value) of each 3D model from semi-automatic set, automatic set, oblique images and ALS had been measured. All four listed datasets (semi-automatic set, automatic set, oblique images and ALS) had been geo-referenced in Dutch coordinate system. So, the comparison between highest elevation points of each of the 3D models in all these four datasets would be possible. In this situation, highest elevation points were measured with helps of Autodesk® AutoCAD software for semi-automatic set and automatic set, Autodesk® Image modeller software for oblique images and PCM software for ALS. In the following Table 21, the highest elevation point of each 3D model is shown.

Model	Automatic models	Semi-automatic models	ALS (input)	Oblique images
T1A	44.32m	45.48m	45.48m	45.54m
T1B	**47.53m**	49.40m	49.55m	49.18m
T1C	46.59m	47.16m	47.20m	47.03m
T2A	47.80m	47.97m	48.20m	48.10m
T2B	-	48.90m	48.97m	49.23m
T2C	44.39m	44.39m	44.53m	44.36m
T3A	49.61m	49.62m	49.63m	49.48m
T3B	**44.32m**	47.23m	47.24m	47.13m
T3C	48.28m	48.28m	48.34m	48.13m
T4	49.56m	49.55m	49.67m	49.53m
T5A	51.38m	51.39m	51.44m	51.08m
T5B	49.50m	49.28m	49.29m	49.25m
T5C	52.04m	52.04m	52.13m	52.03m
T6A	55.52m	55.50m	55.50m	55.37m
T6B	53.15m	53.15m	53.15m	52.91m
T6C	51.98m	51.95m	51.98m	51.64m
T7A	49.98m	49.97m	50.07m	49.83m
T7B	-	-	-	-
T7C	50.28m	50.27m	50.30m	50.07m
T8A	52.46m	52.72m	52.54m	52.33m
T8B	51.84m	51.83m	51.83m	51.78m
T8C	53.46m	53.40m	53.49m	53.01m

Table 21: Lists highest elevation points of each 3D model in semi-automatic set, automatic set, oblique images and ALS.

Table 21 shows that all measured highest elevation points of each 3D model are close to each other, except T1B and T3B of automatic set. Highest elevation points of T1B and T3B in automatic set had differences with others because these two models were reconstructed incorrectly in automatic set. As it is showing in Figure 55, T1B and T3B that were reconstructed in automatic set are showing with green colour and their highest elevation value are showing with blue colour; in this figure, also schematic shape of these two buildings in reality have been shown and highest elevation values from reference have been shown with red colour. It can be concluded that, except T1B and T3B that were incorrectly reconstructed in automatic set, the differences between other values were low. So the results of comparing highest elevation values were satisfactory.

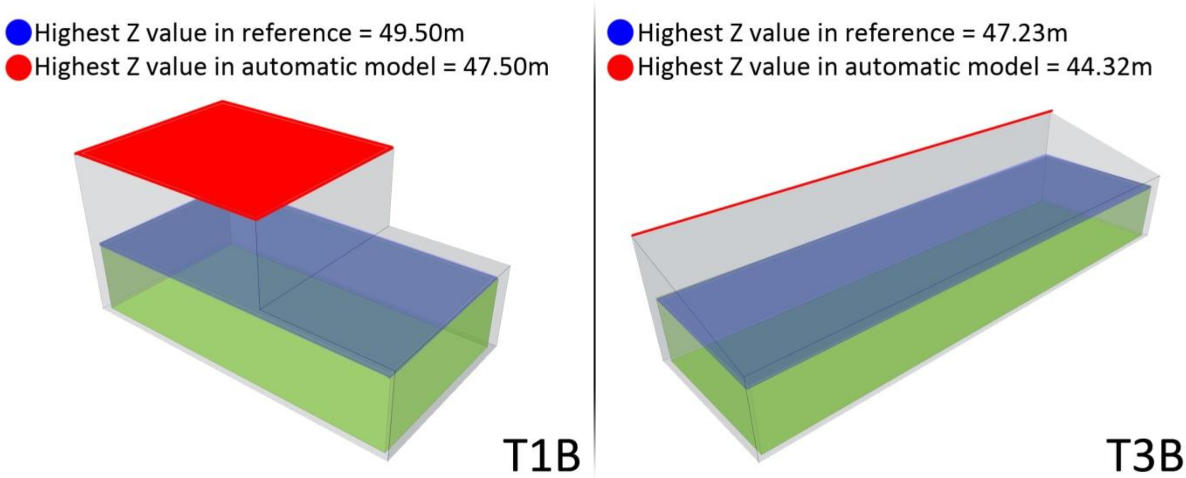


Figure 55: Shows highest elevation values of T1B and T3B that were incorrectly reconstructed in automatic set.

Results of comparison between the highest elevation points of each dataset with other datasets are showing in the following Table 22.

Between highest value of	Maximum difference	RMS differences	RMS differences (without T1B and T3B)
Automatic and semi-automatic models	2.91m (T3B)	0.83m	0.32m
Automatic models and ALS dataset	2.92m (T3B)	0.85m	0.33m
Automatic models and oblique images	2.81m (T3B)	0.81m	0.37m
Semi-automatic models and ALS dataset	0.23m	0.09m	-
Semi-automatic models and oblique images	0.39m	0.20m	-
ALS dataset and oblique images	0.48m	0.23m	-

Table 22: Shows the results of comparison between the highest elevation points of each dataset with others.

As it were mentioned in Table 22, each dataset was compared with other datasets. From the results of these comparisons the following results would be concluded:

If ALS would be assumed as dataset with high accuracy in heights, with comparison between the results of RMS differences between highest value of semi-automatic models and ALS and RMS differences between highest value of automatic models and ALS it would be determined that semi-automatic method would be reconstructed models with better height accuracy in comparison with automatic method.

Due to small amount of RMS differences between highest values of semi-automatic models and ALS dataset and also assumption of ALS as high accuracy dataset in heights, so it can be concluded that systematic error in semi-automatic method is low. And also by comparing the results of RMS differences between highest values of semi-automatic models and automatic models (except T1B and T3B) it can be concluded that systematic errors had more effects in results of automatic models.

4.2.4.4. Quality report

As it were described briefly in this chapter, for each of the 3D model from both semi-automatic and automatic sets of 22 selected reconstructed models, introduced quality aspects were assessed. After assessing topology correctness, roof related aspects, dormer related aspects and body related aspects for each 3D model individually, preparing quality report of each model would be possible. On the other words, quality report is summary of results of quality assessments for each 3D model. In this case, by having quality report for each 3D model, discuss about the quality of that specific 3D model would be possible. In the following Table 23, quality reports of each of the 22 reconstructed 3D models in semi-automatic set are showing individually.

			Dormer part			Body part									Height accuracy		
						Positional accuracy			Footprint								
Model	**Topology correctness**	**Roof similarity**	Reconstruction rate (%)	RMS Depth (meter)	RMS Length (meter)	RMS X differences (m)	RMS Y differences (m)	RMS D differences (m)	Footprint correctness	Matched overlay (%)	Area omission (%)	Area commission (%)	Area differences (sqm)	Perimeter differences (m)	Difference with ALS	Difference with Automatic	Difference with oblique
T1A	Yes	-	-	-	-	0.12	0.11	0.16	No	93	7	8	0.96	0.30	0.00	1.16	0.06
T1B	Yes	-	-	-	-	0.44	0.40	0.59	Yes	99	0	0	0.01	0.01	0.15	1.87	0.22
T1C	Yes	-	-	-	-	0.43	0.24	0.49	Yes	100	0	0	0.08	0.04	0.04	0.57	0.13
T2A	Yes	-	-	-	-	0.47	0.72	0.84	-	-	-	-	-	-	0.23	0.17	0.13
T2B	Yes	-	-	-	-	0.51	1.61	1.12	-	-	-	-	-	-	0.07	-	0.33
T2C	Yes	-	-	-	-	1.93	0.70	1.21	No	100	0	0	0.08	0.04	0.14	0.00	0.03
T3A	Yes	Yes	-	-	-	0.30	0.20	0.36	Yes	99	1	4	3.89	1.82	0.01	0.01	0.14
T3B	Yes	Yes	-	-	-	0.15	0.45	0.47	No	99	0	0	0.11	0.03	0.01	2.91	0.10
T3C	Yes	Yes	-	-	-	0.11	0.12	0.17	Yes	100	0	0	0.14	0.07	0.06	0.00	0.15
T4	Yes	Yes	-	-	-	0.17	0.26	0.54	Yes	100	0	9	9.42	3.94	0.12	0.01	0.02
T5A	Yes	No	-	-	-	0.24	0.20	0.55	No	88	0	0	0.01	0.00	0.05	0.01	0.31
T5B	Yes	No	-	-	-	0.49	0.23	0.54	No	100	0	0	0.18	0.09	0.01	0.22	0.03
T5C	Yes	No	-	-	-	0.14	0.05	0.15	No	100	0	11	12.52	6.06	0.09	0.00	0.01
T6A	No	No	100	0.09	0.28	0.39	0.34	0.70	No	98	0	0	0.02	0.01	0.00	0.02	0.13
T6B	Yes	No	-	-	-	5.21	10.20	11.45	-	-	-	-	-	-	0.00	0.00	0.24
T6C	No	No	-	-	-	6.33	0.52	1.89	No	89	11	14	4.33	171.97	0.03	0.03	0.31
T7A	Yes	Yes	100	0.30	0.16	0.24	0.11	0.26	No	94	0	0	0.07	0.04	0.10	0.01	0.14
T7B	Yes	Yes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T7C	Yes	Yes	100	0.12	0.06	0.19	0.13	0.23	No	91	9	23	17.34	5.81	0.03	0.01	0.20
T8A	Yes	Yes	100	0.06	0.12	0.89	0.15	0.76	No	100	0	0	0.24	0.09	0.18	0.26	0.39
T8B	Yes	No	100	0.39	0.31	0.72	0.18	0.71	No	100	0	0	0.10	0.06	0.00	0.01	0.05
T8C	Yes	Yes	25	0.14	0.94	0.23	0.11	0.48	No	100	0	30	42.49	18.00	0.09	0.06	0.39

Table 23: Shows quality reports of each of the 22 reconstructed 3D models in semi-automatic set.

Summary of quality assessments of automatic models can be listed in same table as quality reports of each of the 22 reconstructed 3D models in automatic set. These results are showing in the following Table 24.

			Dormer part			Body part									Height accuracy		
						Positional accuracy			Footprint								
Model	**Topology correctness**	**Roof similarity**	Reconstruction rate (%)	RMS Depth (meter)	RMS Length (meter)	RMS X differences (m)	RMS Y differences (m)	RMS D differences (m)	Footprint correctness	Matched overlay (%)	Area omission (%)	Area commission (%)	Area differences (sqm)	Perimeter differences (m)	Difference with ALS	Difference with Semi-auto	Difference with oblique
T1A	Yes	Yes	-	-	-	-	-	-	-	-	-	-	-	-	1.16	1.16	1.22
T1B	Yes	Yes	-	-	-	-	-	-	No	98	2	46	81.35	55.55	2.02	1.87	1.65
T1C	Yes	Yes	-	-	-	0.25	0.18	0.31	Yes	92	8	0	7.52	3.83	0.61	0.57	0.44
T2A	Yes	Yes	-	-	-	0.46	0.43	0.63	No	98	2	2	0.37	12.45	0.40	0.17	0.30
T2B	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T2C	Yes	Yes	-	-	-	1.72	0.52	1.80	No	86	13	0	13.50	6.77	0.14	0.00	0.03
T3A	No	Yes	-	-	-	0.15	0.23	0.27	Yes	99	1	2	0.88	0.33	0.02	0.01	0.13
T3B	Yes	No	-	-	-	-	-	-	-	-	-	-	-	-	2.92	2.91	2.81
T3C	No	Yes	-	-	-	0.13	0.16	0.21	Yes	92	8	0	7.76	3.90	0.06	0.00	0.15
T4	Yes	No	-	-	-	2.85	0.19	2.86	No	99	1	28	36.53	13.43	0.11	0.01	0.03
T5A	Yes	No	-	-	-	0.55	0.83	1.00	No	84	16	0	15.74	3.13	0.06	0.01	0.30
T5B	No	No	-	-	-	0.41	2.16	2.20	No	66	0	52	34.39	17.97	0.21	0.22	0.25
T5C	Yes	No	-	-	-	0.91	0.10	0.91	No	82	0	22	18.17	9.80	0.09	0.00	0.01
T6A	No	Yes	0	-	-	1.40	1.16	1.82	No	84	16	2	14.40	20.20	0.02	0.02	0.15
T6B	Yes	No	-	-	-	0.38	0.25	0.45	Yes	94	6	2	3.89	1.44	0.00	0.00	0.24
T6C	Yes	No	-	-	-	2.15	0.77	2.29	No	86	14	4	10.50	7.51	0.00	0.03	0.34
T7A	Yes	Yes	66	0.15	0.32	0.55	0.33	0.64	No	89	11	0	10.74	5.44	0.09	0.01	0.15
T7B	Yes	Yes	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
T7C	No	Yes	100	0.31	0.11	0.23	0.24	0.33	No	92	8	0	7.88	3.95	0.02	0.01	0.21
T8A	No	No	100	0.66	0.07	0.26	1.03	1.06	No	95	5	13	9.88	6.53	0.08	0.26	0.13
T8B	No	No	33	0.55	0.09	0.13	0.25	0.28	No	90	10	1	9.02	7.39	0.01	0.01	0.06
T8C	No	Yes	0	-	-	0.22	0.08	0.23	No	88	12	0	12.22	10.42	0.03	0.06	0.45

Table 24: Shows quality reports of each of the 22 reconstructed 3D models in automatic set.

From the prepared quality report of each of the 22 reconstructed 3D models (results of Table 23 and Table 24), preparing quality report for whole set of these selected models would be possible for both semi-automatic and automatic sets of models. In this case, as it were described before, by calculating average of the results of each quality aspects and introduces indices, preparing quality report for whole set of 22 models would be possible. In Table 25 quality reports for whole set of 22 models reconstructed with semi-automatic method and automatic method are showing individually.

Quality aspect		Semi-automatic set	Automatic set	Reference
Topology correctness		90.90%	66.66%	-
Roof part	Roof similarity	58.80%	40.00%	Oblique images
Dormer part	Reconstruction rate	93.00%	35.00%	Oblique images
	Average of RMS depth	0.24m	0.30m	Nadir images
	Average of RMS length	0.23m	0.26m	Nadir images
Positional accuracy	Average of RMS X	0.39m	0.51m	Nadir images
	Average of RMS Y	0.32m	0.47m	Nadir images
	Average of RMS Distance	0.58m	0.74m	Nadir images
Footprint	Equal segments	88.88%	55.55%	Cadastral 2D maps
	Average of RMS length	0.58m	0.89m	Cadastral 2D maps
	Footprint correctness	27.00%	22.22%	Cadastral 2D maps
	Matched overlay	97.27%	89.73%	Cadastral 2D maps
	Area omission error	1.57%	7.28%	Cadastral 2D maps
	Area commission error	5.55%	9.66%	Cadastral 2D maps
	Area difference	1.31sqm	9.50sqm	Cadastral 2D maps
	Perimeter difference	1.21m	6.42m	Cadastral 2D maps
Height accuracy	RMS of differences between highest value of model and reference	0.09m	0.33m	ALS
		0.20m	0.37m	Oblique images
		0.32m	-	Automatic models
		-	0.32m	Semi-automatic models

Table 25: Shows quality reports for whole set of 22 models reconstructed with semi-automatic method and automatic method and also lists used reference dataset for assessing each aspect.

After preparing quality report for whole set of 22 models in both semi-automatic and automatic sets, the results of each quality aspect of whole semi-automatic set and automatic set will be showing in Figure 56. In this figure, the results of each aspect were determined from 0 to 100. There isn't any problem for determination aspects that their results are in percentage (such as topology correctness and dormer's reconstruction rate). But In Figure 56 for determining values of RMS differences, maximum value of RMS difference is assumed as 0 and the minimum value of RMS difference is assumed as 100 (contrast ratio). On the other words, if for example the maximum of all calculated RMS value was 0.50m and RMS of one of the aspects was 0.40m, then in this figure, 0.40m determined equivalent as 20 out of 100 (0.50m would be assumed as 0 and 0.00m would be assumed as 100).

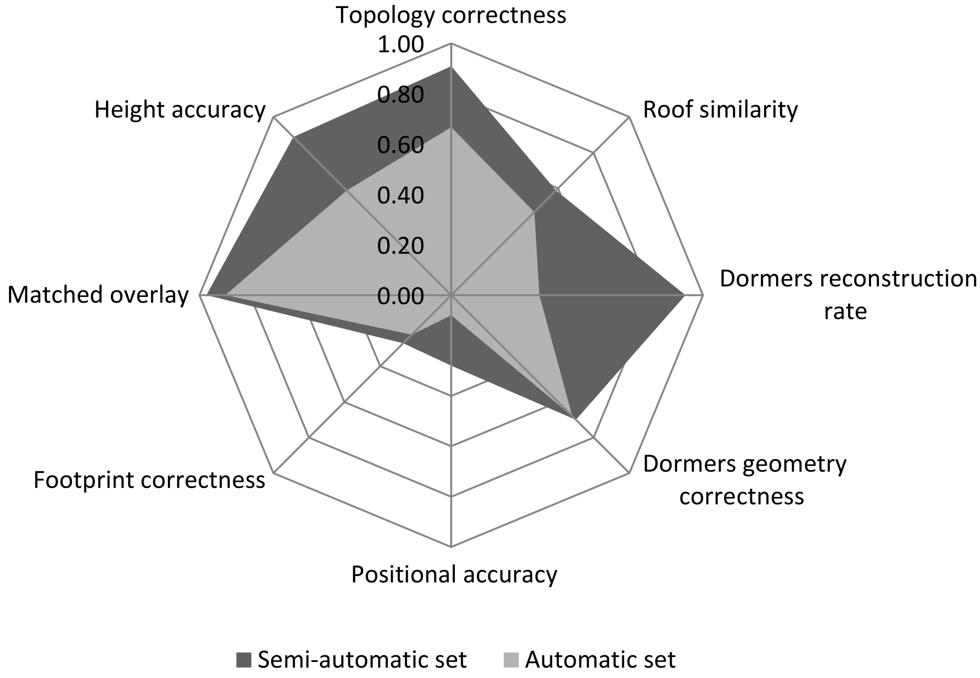


Figure 56: Comparison between quality report of semi-automatic and automatic set of 22 models.

From Figure 56 that compares quality reports between semi-automatic and automatic sets of models, it can be concluded that semi-automatic models have better quality in all aspects in comparison with automatic models. But it doesn't mean that automatic models are incorrect and as it were mentioned in chapter two, correctness of each 3D model or sets of 3D models depends on user's requirements. On the other words, by analyzing the results of quality reports of each set and compare them with user's requirements, judgment about the correctness of models and usability of reconstruction method would be possible for users. In addition, it must be mention that, reconstruction models in automatic method are faster than semi-automatic method; and reconstruction models in semi-automatic method is time consuming and also depends on modeller's knowledge and his/her experiments.

From prepared quality report of 22 selected 3D models, estimation accuracy of each introduced quality aspects would be possible. In this case, from available quality report of 22 semi-automatic models it can be concluded that with used ALS as input dataset and with helps of PCM software, reconstructed models usually have correctness in their topology, their roof shape almost be similar as their reference, dormers usually reconstructed well with good geometry accuracy and positional accuracy and footprint correctness depends on overhangs of the building in reality, because in this method there isn't any mention on overhangs. Heights of 3D models that reconstructed with semi-automatic method are near their input dataset and the accuracy of height is well. But models that reconstructed with automatic method because of using cadastral 2D maps alongside ALS as their input datasets are usually have better results in footprint correctness and positional accuracy (these results also depends on quality of cadastral 2D maps). For simple roof shapes, automatic reconstructed models have similar roof shapes in comparison with reality.

In the end for selecting useful reconstruction method or input dataset, it is recommended to prepare quality report (by assessing introduced quality aspects) for some sample models that were reconstructed with selected reconstruction method and input dataset. If the quality of sample reconstructed models were admissible in comparison with user's requirements, then it can be concluded that the models that will be reconstruct from used reconstruction method and used input dataset would be acceptable for user's work and will meet their needs.

For comparing between prepared quality report of set of models and user's requirements, mentioning on the used reference datasets for assessing each quality aspect for prepared quality report is important. Used reference dataset must be the most accurate dataset from available datasets for assessing each aspect; and in comparison between two quality reports (for example for comparing two reconstruction methods and choosing better one) used reference datasets for assessing each quality aspect must be same in both quality reports.

4.3. Automatically derived quality measures of automatic models

In automatic method of reconstruction 3D models 3.3.2), some quality measures can automatically generated during the reconstruction process (Oude Elberink and Vosselman 2010b). Automatically generated quality measures have been calculated for each building. In this thesis, the following automatic generated quality measures will be used for further comparisons and discussions:

A. The orthogonal distance between laser points and its corresponding roof face.

B. The segments that have not been used in reconstruction process.

The following Figure 57 shows quality measures that were automatically generated during automatic reconstruction process in the test area.

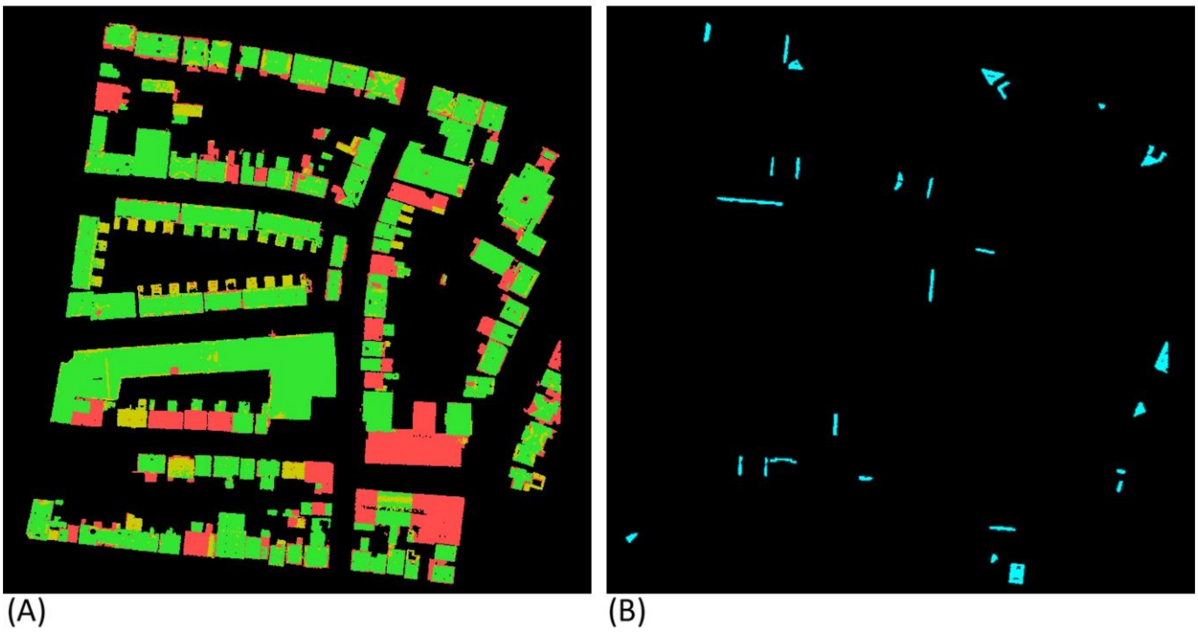


Figure 57: Shows automatic generated quality measures of test area.

As it were shown Figure 57 (A), the orthogonal distances between laser points and its corresponding roof faces were shown by threshold values. In this case, buildings with orthogonal distance less than 20cm were shown in green color. Yellow buildings are buildings with orthogonal distance between

20cm and 50cm. buildings with orthogonal distance more than 50cm were shown with red color. Moreover, in Figure 57 (B), segments that were not used in the automatic reconstruction process were shown. These segments didn't fit to a certain target graph of automatic reconstruction algorithm. The reason these segments were left out from reconstruction process in because of the algorithm did not found any relation between these segments and the target graphs that used in matching algorithm (Oude Elberink and Vosselman 2010b).

In the following, results of quality measures that automatically generated during reconstruction process will be compared with some related quality aspects that were assessed in previous paragraphs of this chapter. These comparisons will be done for 22 selected building models that were automatically reconstructed.

A. Discussion between assessed quality aspects and calculated orthogonal distances:

As it were mentioned before, orthogonal distances between laser points to its corresponding roof face were generated automatically for models in test area. Nine of the 22 selected models had red colour parts in this automatic generated quality measure. That means, nine of the models had at least one big roof face with more than 50cm difference with its corresponding laser points. These nine models are T1A, T1B, T1C, T3B, T5A, T6A, T8A, T8B and T8C. In the following Table 26 the results of roof similarity and height accuracy of these models is showing.

Models with not used segments		Assessed quality aspects related to roof part
1	T1A	Have height differences more than 50cm in comparison with ALS (Table 21).
2	T1B	
3	T1C	
4	T3B	Assessed not similarity in roof part 4.2.2.1).
5	T5A	Assessed not similarity in roof part 4.2.2.1).
6	T6A	The tower of church was not reconstructed.
7	T8A	Assessed not similarity in roof part 4.2.2.1).
8	T8B	Assessed not similarity in roof part 4.2.2.1).
9	T8C	One big dormer was not reconstructed (2.3.3.1). Roof is similar but has been generalized.

Table 26: Shows list of models with orthogonal distance more than 50cm.

As it is showing in Table 26, four of the models with red colours in their roof faces were not similar in their roof part. Three flat roofs have height differences more than 50cm in comparison with ALS. Moreover, due to missed tower of church (T6A) and missed dormer of T8C, these two models also have red roof faces. Figure 58 shows models that have at least on roof face with more than 50cm difference with its corresponding laser points.

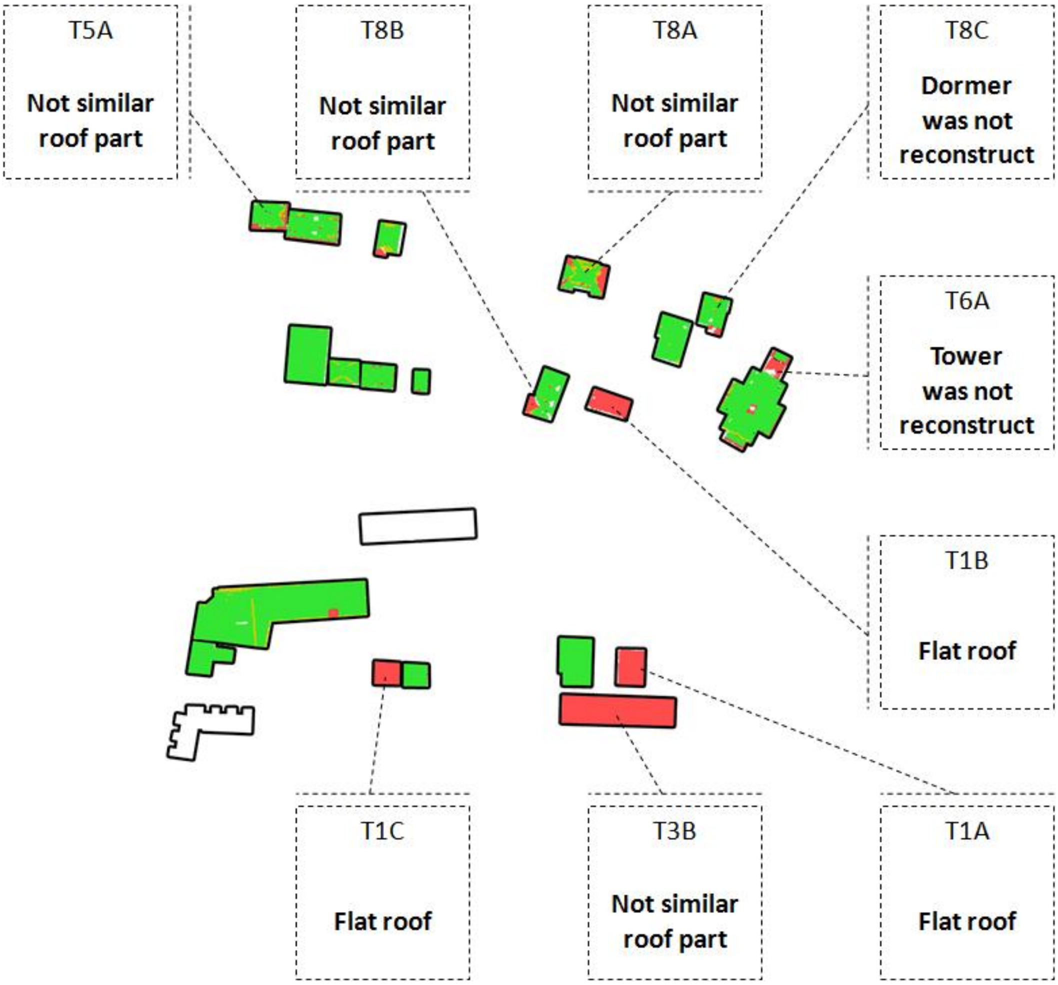


Figure 58: Shows models that have at least on roof face with more than 50cm difference with its corresponding laser points and their quality assessments.

So it can be concluded that, models that have more than 50cm orthogonal distances between laser points to its corresponding roof face would have problems in their roof similarity or in reconstructing some parts of their body (dormers or body parts). In the case of flat roofs, because of step edges, height differences are more than 50cm.

B. Discussion between assessed quality aspects and not used segments:

As it were mentioned before, one of the automatic generated quality measures was segments that were not used in reconstruction process (Figure 57, B). In this test area, as it were shown in Figure 57 (B), 30 segments were not used in automatic reconstruction process. On the other hand, from 22 selected buildings, six of them include 10 segments that were not used for their reconstruction. These six models are: T5A, T5B, T6A, T6C, T8A and T8C. In the following Table 27, roof similarity of these six models that includes some not used segments is showing.

Models with not used segments		Assessed quality aspects related to roof part	Number of not used segments
1	T5A	Assessed not similarity in roof part 4.2.2.1).	1
2	T5B	Assessed not similarity in roof part 4.2.2.1).	2
3	T6A	The tower of church was not reconstructed.	1
4	T6C	Assessed not similarity in roof part 4.2.2.1).	3
5	T8A	Assessed not similarity in roof part 4.2.2.1).	2
6	T8C	One big dormer was not reconstructed (2.3.3.1).	1

Table 27: Lists roof similarity of models that include not used segments in their reconstruction process.

As it were mentioned in Table 27, all of the six models that include not used segments in their reconstruction have problems in their shapes. Four of them (T5A, T5B, T6C and T8A) as were assessed before have not similarity in their roof part. Church tower (T6A) was totally missed because of not using some segments in its reconstruction process. Also one big size dormer (T8C) was not reconstructed because of not using its segment in reconstruction process. The following Figure 59 shows models that include not used segments and their quality assessments of their roof parts.

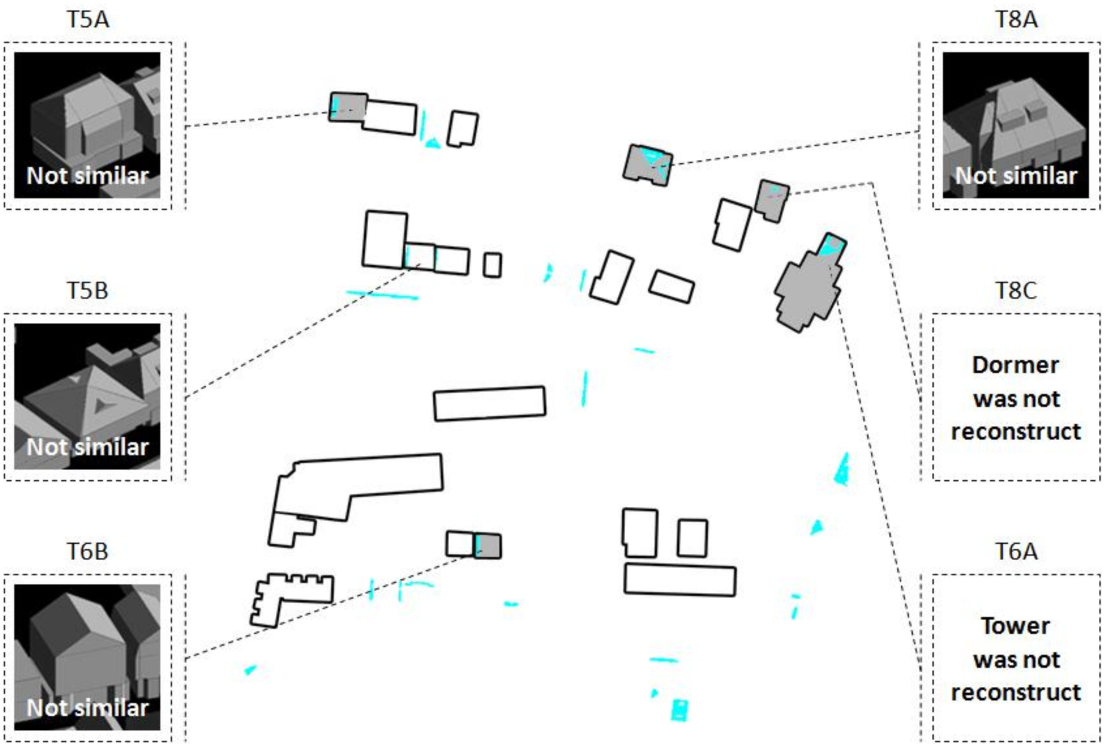


Figure 59: Shows models that include not used segments and their quality assessments of their roof parts.

So it can be concluded that, models that includes not used segments in their automatic reconstruction process would have problems in their roof similarity or in reconstructing some parts of their body (dormers or body parts).

By having these two comparisons between assessed quality aspects of models and automatic generated quality measures, the following results are concluded:

- As it were assessed in roof similarity section (4.2.2.1), Figure 46, nine automatic reconstructed models have no similarity in their roof part. Four of them had segments with more than 50cm orthogonal distances to its corresponding laser points, two of them were included not used segments and two of them are in both automatic generated quality measures. So, seven of all 9 not similar roofs were determined from automatic generated quality measures. The reason for not detecting other two not similar models (T6B and T4) is because of in T6B all roof faces were used in reconstruction process but slide roofs were reconstructed as walls. In T4, roof part was extruded outside of the footprint and that is the reason of having not similar roof part in T4 (reconstructed roof had similarity inside footprint of model).
- Models with segments with more than 50cm orthogonal distances to its corresponding laser points usually have problems. These problems occur because of differences in heights, missed reconstructed parts or having no similar roofs.
- Finally it can be concluded that, instead of selecting some sample models for estimating the quality of whole set of automatic models, checking the quality of models that include not used segments in their reconstruction process and/or models with red roof segments (difference more than 50cm) would be useful for finding the critical models that have problems in their roof shapes or have low height accuracy.

4.4. Summary

For assessing quality of each 3D model, different aspects were introduced in chapter two. Introduced aspects were: topology check and aspects related to roof part, dormer part and body part of each 3D model. On the other hand, in chapter three, two sets of model were reconstructed from ALS as their input dataset and by using semi-automatic and automatic reconstruction method. Each set of models contains 22 buildings with various types of footprints and roof shapes. In this chapter, quality of each of the 22 selected building in both sets of models was assessed. Reference dataset were selected from available datasets for each quality aspect. The selected reference dataset for each aspect was the best choice for assessing quality of that aspect in comparison with other available datasets because of its specifications. For each model, topology check, roof shape similarity, geometry of roof part, dormer's reconstruction rate, geometry of dormer, positional accuracy, footprint correctness and related indices and height accuracy were assessed. After assessing these aspects for each 3D model, quality report for each 3D model in both sets were prepared. From the prepared quality reports, quality report for whole set of 22 models were prepared too. From the results of each aspect, pros and cons of each reconstruction method were discussed in this chapter. Finally by available quality report of each set of models, estimating quality report for each reconstruction method (semi-automatic and automatic) would be possible. Also judgment about usability of reconstruction methods, used input datasets and usability (and/or correctness) of reconstructed models would be possible by having comparison between quality report and user's requirements.

Moreover, assessed quality aspects of 22 selected building models in automatic set were compared by quality measures that were automatically generated during the reconstruction process. Automatic generated used quality measures were segments that were not used in reconstruction process and classification of models by their orthogonal distance between their roof faces and its corresponding laser points. From the results of these comparisons it can be concluded that, instead of selecting some sample models for estimating the quality of whole set of automatic models, checking the quality of models that include not used segments in their reconstruction process and/or models with red roof segments (difference more than 50cm) would be useful for finding the critical models that have problems in their roof shapes or have low height accuracy.

5. Conclusions and recommendations

5.1. Conclusions

The main objective of this thesis was to propose quality aspects which cover more perspectives of 3D models reconstructed from ALS. Based on the assessment results of semi-automatic and automatic sets of models, the research questions are addressed.

Deeper insight for assessing quality of 3D building models had been done. For this purpose, different quality aspects were introduced for building parts separately (roof, dormer and body). Apart from building parts, topological characteristics of the models were checked. By these assessments, for each 3D model, its quality report was prepared.

The first and second questions are dealing with available standards about quality and proposing some quality issues which consider more aspects of 3D building models.

About the context of quality for 3D building models, a few number of standards were available which are not quite comprehensive. In order to overcome this fact, eight different quality aspects were proposed. Each of these aspects are introduced in chapter 2, assessment method and their reference are also discussed. These aspects are: (1) Topology, (2) Roof similarity, (3) Geometry of roof, (4) Dormer's reconstruction rate, (5) Geometry of dormers, (6) Positional accuracy, (7) Footprint correctness with its related indices and (8) height accuracy.

Third and fourth questions are about determining the crucial components which affect the quality of 3D models and the influence of each modeling method (semi-automatic & automatic) on the final quality of reconstructed building models.

The answers of these questions are obtained by comparing the results of assessing quality for both semi-automatic and automatic models. Below is the list of crucial components that shown their influences in the quality of models in each set and the impact of each reconstruction method:

- Roof overhangs of buildings had effects in the results of positional accuracy and footprint correctness in both sets of models. In both semi-automatic and automatic models, body parts of models were reconstructed from roof faces, so, all of these models that had overhangs in reality were reconstructed with the bigger body outlines.
- Human interpretations prevent some ordinary errors in semi-automatic models that may exist in automatic models. In this case, semi-automatic models had better results in roof similarity, dormer's reconstruction rate and footprint correctness when compared with automatic models.
- Moreover, dormer's size had some effects in reconstruction rate of dormers and/or roof similarity in both sets of models. In some cases, in automatic method big dormers were segmented as roof faces, so the reconstructed roof was not similar with its reality.
- Also, shape of roofs had effects in reconstructed roof of models in both semi-automatic and automatic models. E.g. In automatic models, small segments and segments that were not used in reconstruction procedure had effects in shapes of reconstructed roofs, results of roof

similarity and height accuracy. Moreover, in automatic method, because of using the available library with limited number of roof shapes, in some cases, final products had some errors in their roof shape.

- Shape of building's footprint had also effects in results of modeling. In some cases, models that were extruded from complicated footprints had problems in fitting correct roof shapes.

Apart from the mentioned findings, the following conclusions are drawn:

Each user due to his requirements must determine thresholds for making decision about the usability of 3D models (as it was also mentioned in ISO standards); and by comparing user requirements and quality report of 3D models, find out that 3D model(s) would be useful for his work or not. Also making decision about the correctness of 3D model (or set of models) would be possible by having comparison between prepared quality report and user's requirements.

By choosing more accurate references for each of the aspects, the results of the quality assessments will be more accurate compared to reality. I.e. it will be better to compare the quality of 3D building models with more accurate reference datasets.

Before reconstructing 3D models, it is better to check which datasets are available for using as reference. It is also important to check the quality of 3D models with a reference which is acquired in the same time of acquiring the input dataset. Considering this item will help in the case of building demolition or construction in reality.

5.2. Recommendations

The following are the recommendations for further research:

- In this thesis, introduced quality aspects were assessed manually (in some cases visually). Also, workflow of steps of each aspect's assessment was introduced. Further explorations toward automatically assessment of each quality aspects based on introduced UML flowcharts are recommended.

- In this thesis, two sets of models reconstructed with two different reconstruction methods (using same ALS as their data source) were evaluated. Further research is recommended to evaluate 3D building models rebuilt using different ALS data sources with same reconstruction method (i.e. using various ALS datasets with different characteristics for reconstruction). Finally the impact of the different data characteristics on the final product (3D building models) can be observed. This well probably led the researcher to find out about pros and cons of used reconstruction method.

- In this thesis, quality aspects related to roof part, dormer part and body part of the 3D model were proposed. Further consideration on the other parts of the building models such as roof extensions (for example chimney and antenna) are recommended. That would be useful for some users such as users that their works are related to telecommunications.

- This thesis didn't mention on footprints with curve lines and curve roofs such as domes. 3D models of these kinds of buildings are useful in some applications (or for some users). Working on quality aspects of these kind of buildings are recommended.

- Quality aspects related to 3D building models in LOD-2 were introduced in this thesis. Models in different level of details have different characteristics. So, assessing quality of models in LOD-2 has various aspects in comparison with other LODs (such as LOD-3). Further considerations on the quality aspects for models in other LODs are recommended.

- Quality report of sets of models was introduced in this thesis. Further research for collecting various users' requirements is recommended. By collecting and knowing the user's requirements, it would be possible to judge about the correctness of model(s) and to see if the set of 3D models be useful for a certain application of not.

- In this thesis, quality aspects related to 3D building models were introduced. Further research is recommended for collecting and defining quality aspects for other city features such as trees, roads and city furniture. Because other city features are also important in some applications and working on the quality of them is important.

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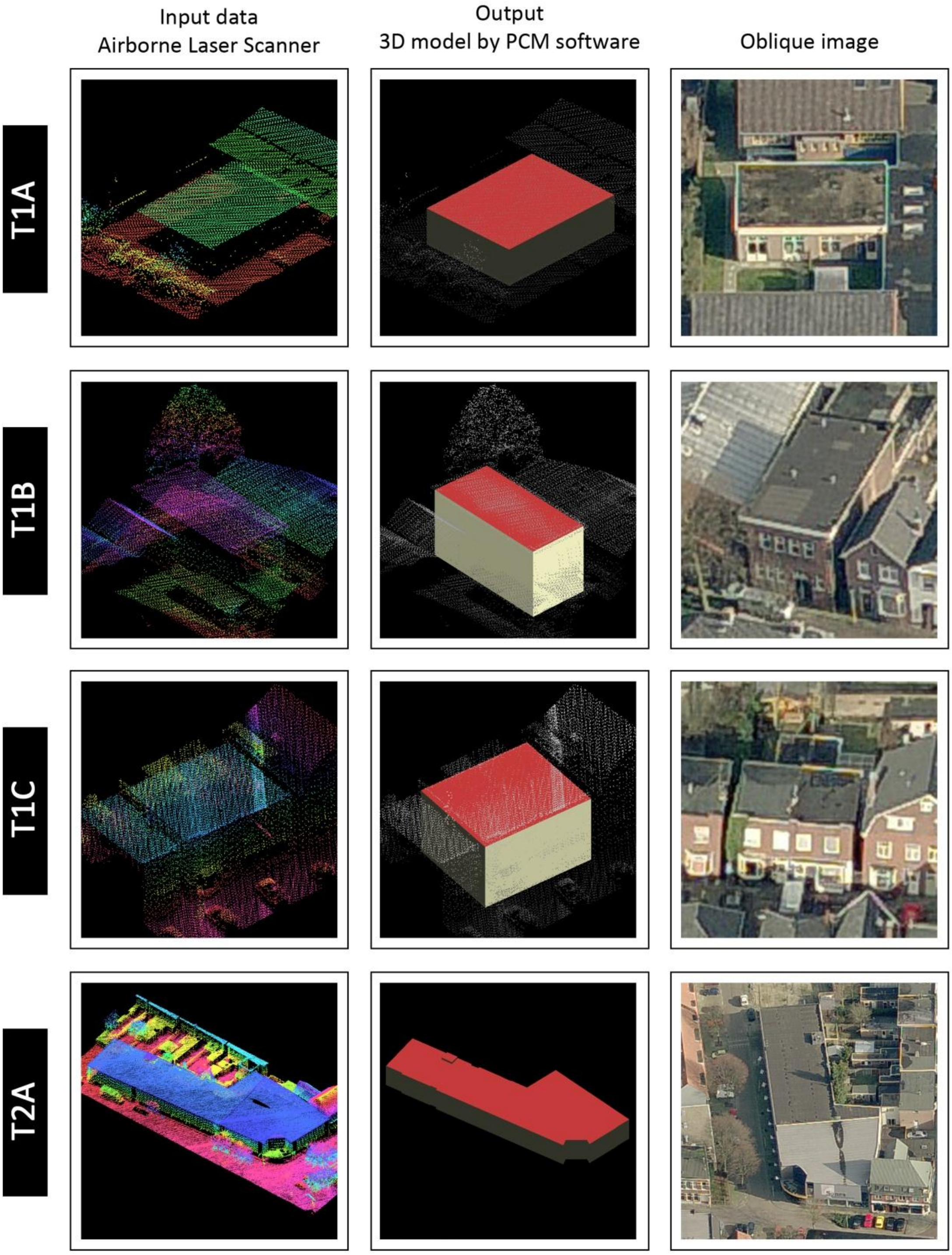
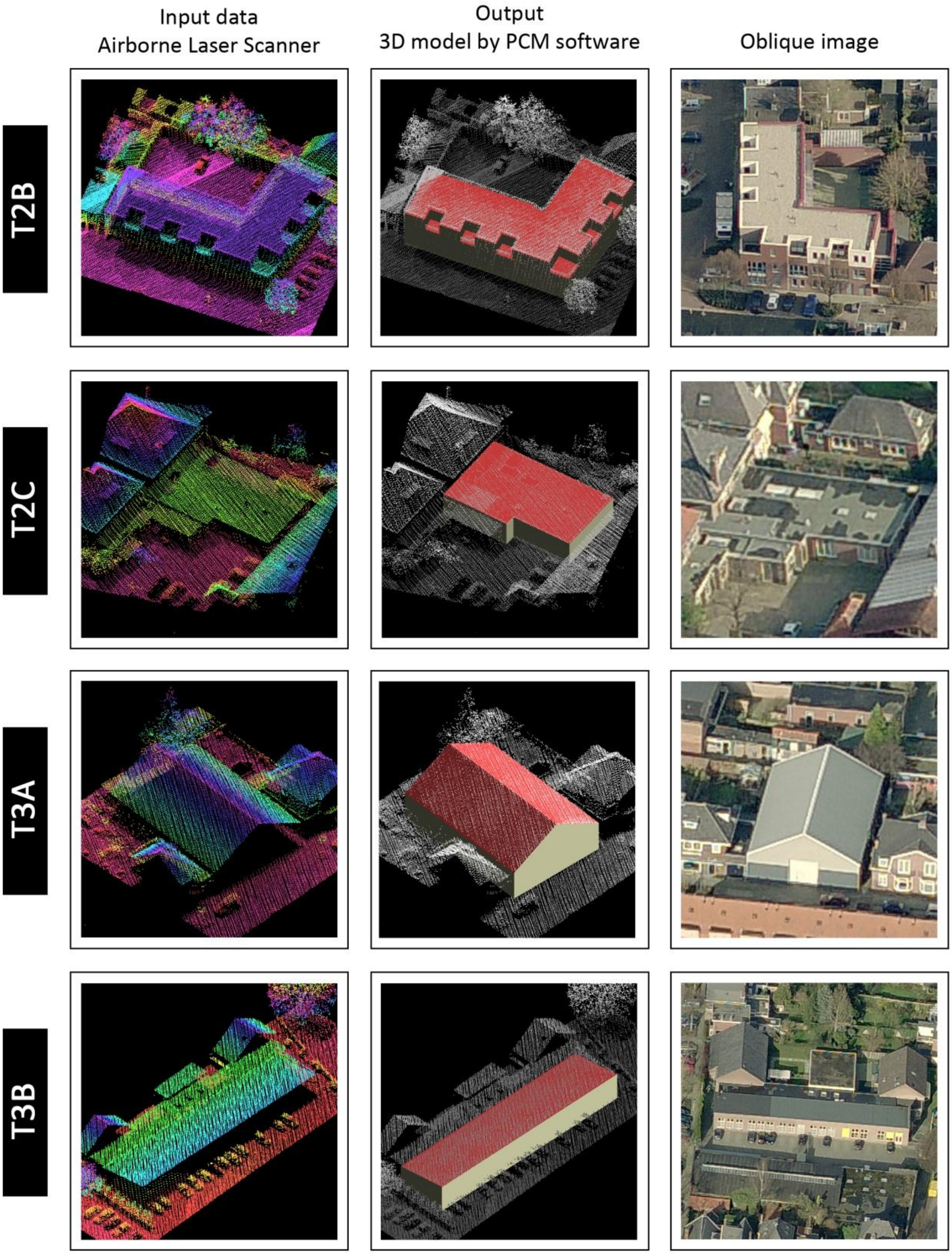
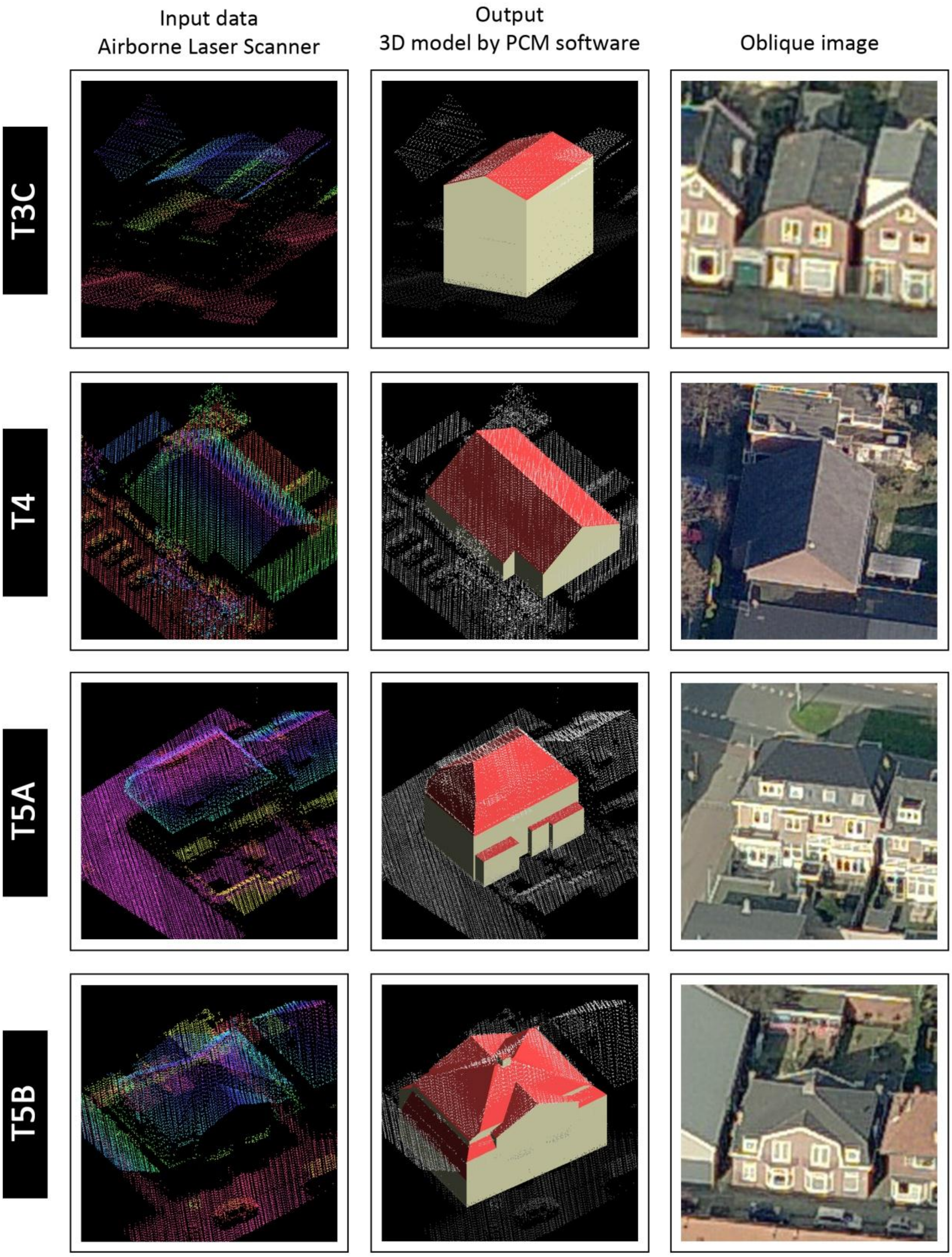
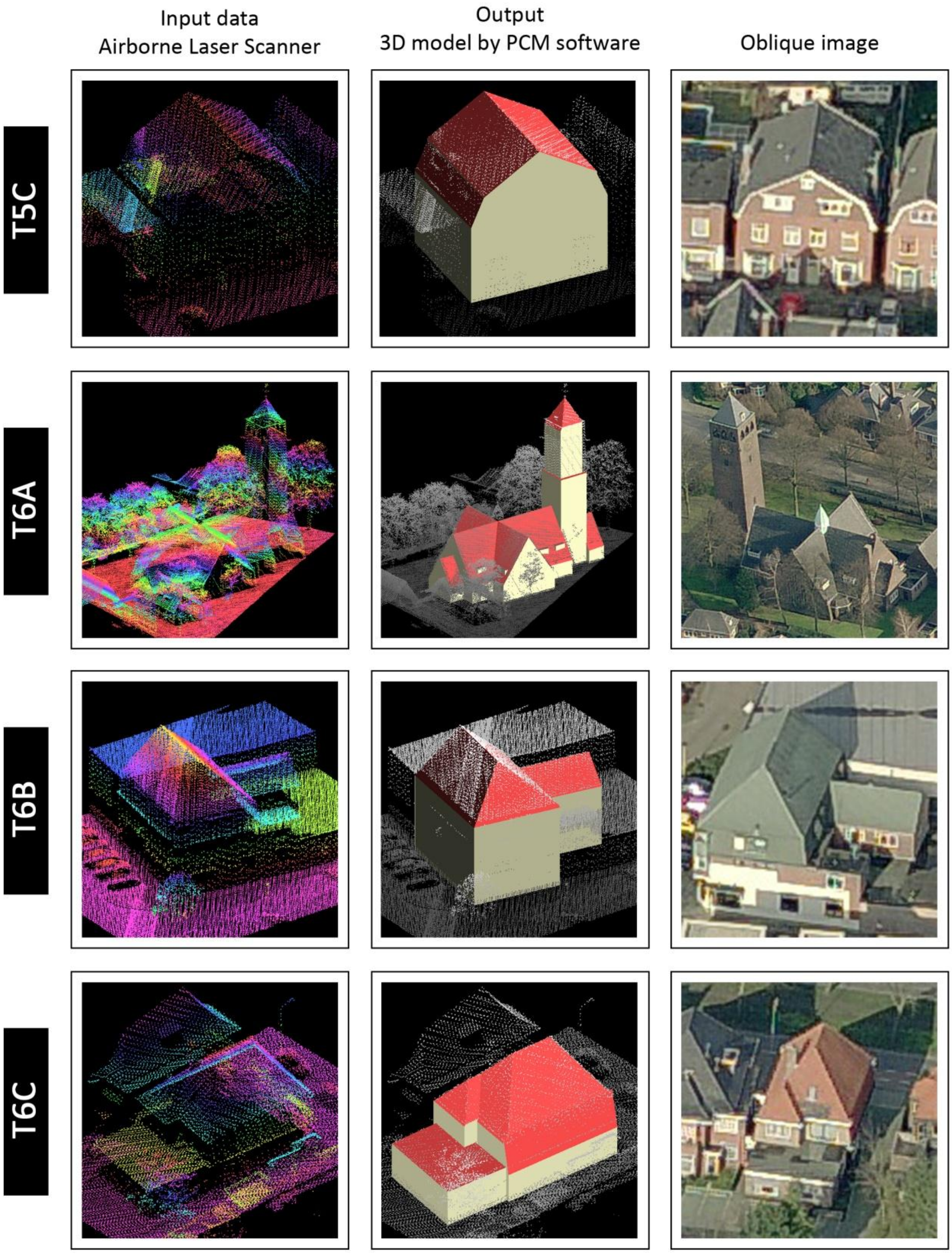
Appendix

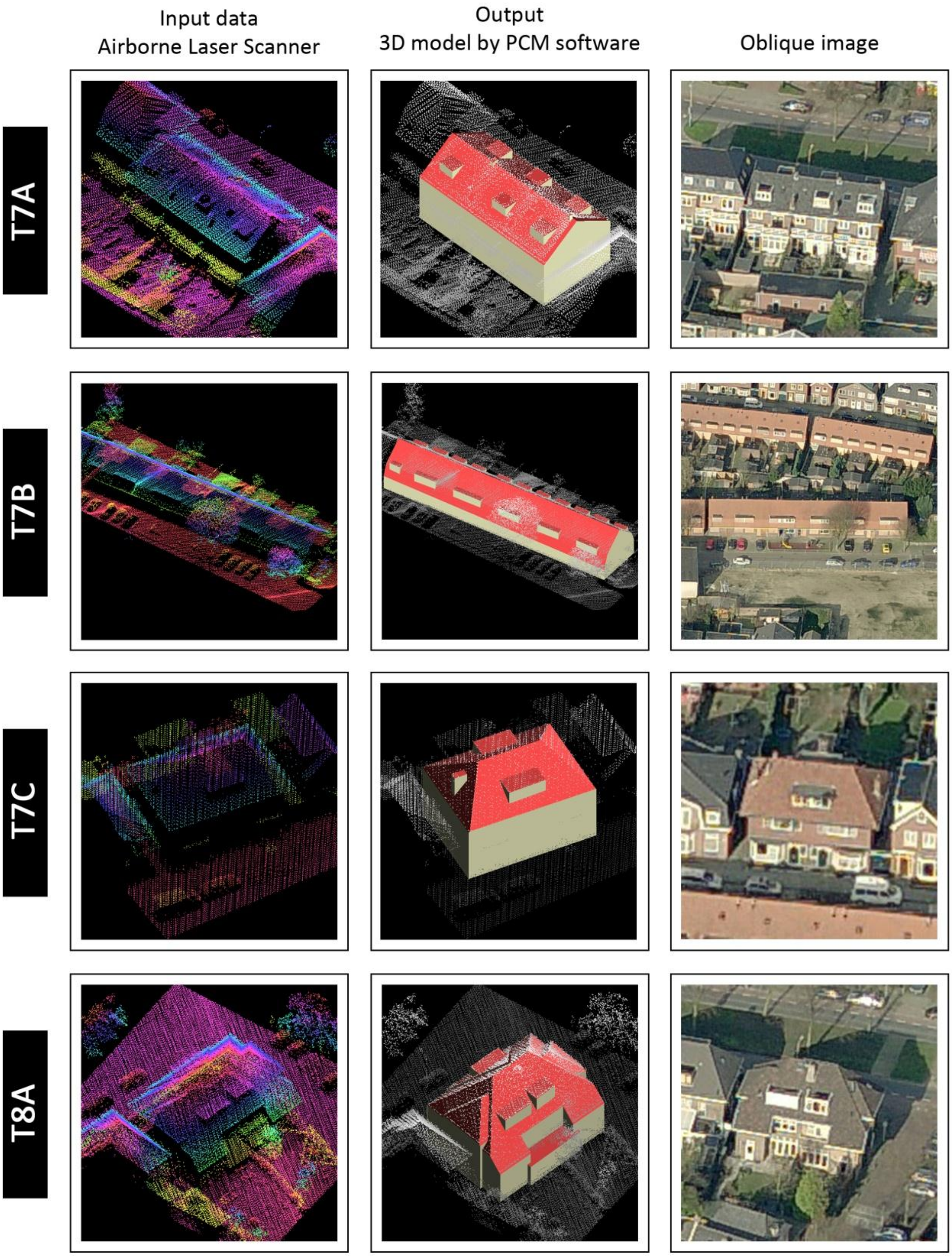
Input data and output 3D model in comparison with oblique images of selected buildings:

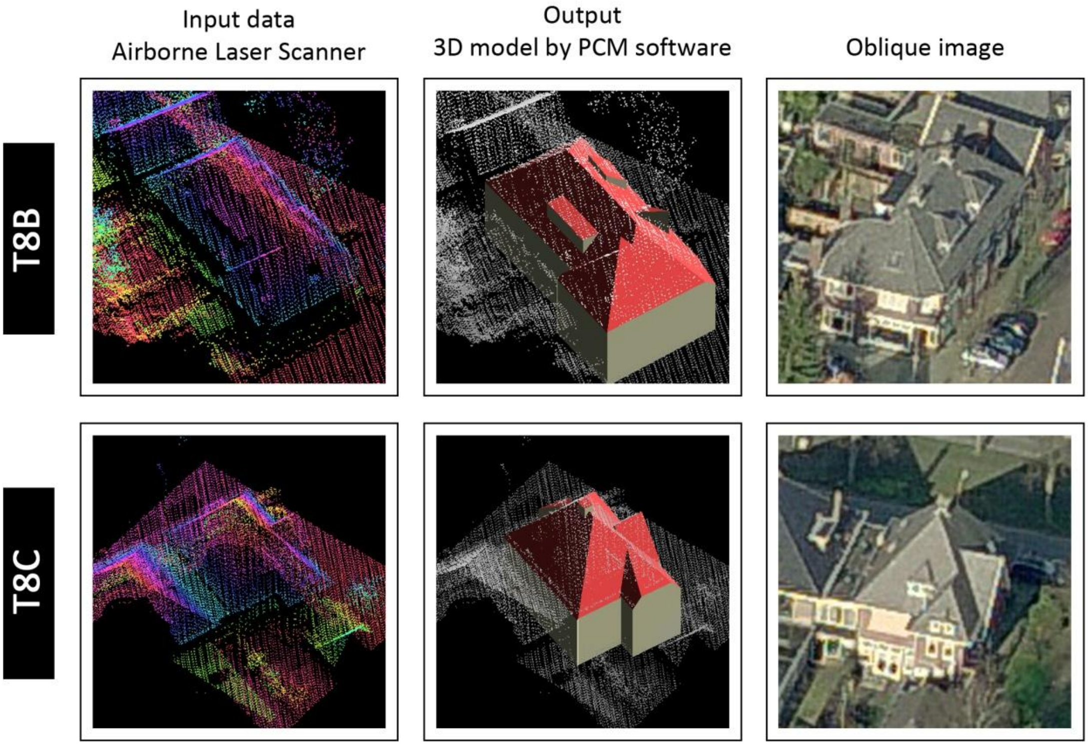



Input data
Airborne Laser Scanner
Output
3D model by PCM software
Oblique image
T2B
T2C
T3A
T3B


Input data
Airborne Laser Scanner
Output
3D model by PCM software
Oblique image
T3C
T4
T5A
T5B


Input data
Airborne Laser Scanner
Output
3D model by PCM software
Oblique image
T5C
T6A
T6B
T6C


Input data
Airborne Laser Scanner
Output
3D model by PCM software
Oblique image
T7A
T7B
T7C
T8A


Input data
Airborne Laser Scanner
Output
3D model by PCM software
Oblique image
T8B
T8C