QUALITY MEASURES FOR BUILDING RECONSTRUCTION FROM AIRBORNE LASER SCANNER DATA

Sander Oude Elberink
Faculty of Geo-information Science and Earth Observation (ITC), University of Twente
Hengelosestraat 99, P.O. Box 6, 7500 AA Enschede The Netherlands
oudeelberink@itc.nl

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ABSTRACT:

As 3D city models become more detailed and more accurate, it is of importance to correctly judge the quality of these models. The problem is that the quality of 3D buildings is composed of multiple indicators that cannot easily fit into a single value. Before analysing differences between reference data and 3D models, it is necessary to understand the realisation of the 3D models. The following study presents criteria to evaluate the quality of reconstructed building models, from a reconstruction point of view. This can be seen as a relative quality check, as no usage has been made of independent reference data. The advantages of the relative quality check are that the quality can be predicted for the complete dataset and that it provides information on which object parts are less accurately reconstructed than others. In this paper we describe several quality measures on buildings that have been reconstructed using airborne laser data. It is shown how the quality measures can be used to gain insight in the quality of the output, but also to improve processing steps along the way from laser data to 3D model. If future users have to indicate if the model is suitable for certain applications, it is advised to deliver these quality measures together with the reconstructed model.

1. INTRODUCTION

Reconstructing buildings in 3D has been a challenging research topic for at least ten years, and will be in future as long as acquisition systems are improving and model requirements are increasing. The tendency is that the reconstructed models become more realistic and more detailed. Once the city model has been created, it is likely that it is stored at a central location, from where multiple users have access to the model. Therefore a description on the quality of the model is necessary in order to decide if the model can be used for certain applications. Only specifying what the Level of Detail (LoD) is does not mean that the geometric accuracy of the model has been determined. Mostly, general parameters such as minimum footprint size and positional accuracy values are mentioned for a certain LoD (Kolbe et al., 2005). However, this does not give an insight in the quality of the specific building models.

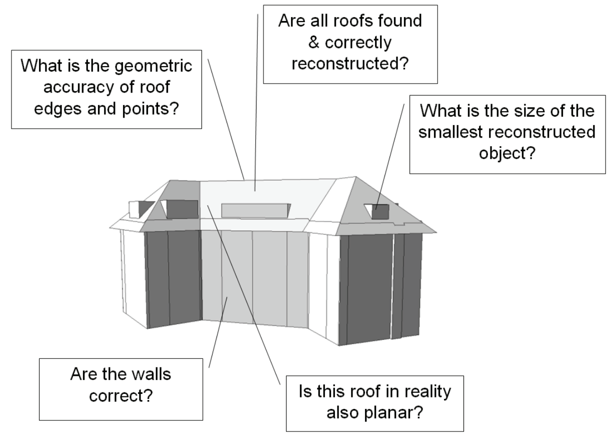

Figure 1. Various questions concerning the quality of 3D buildings.

The problem is that the quality of 3D buildings is composed of multiple indicators that cannot easily fit into a single value. Figure 1 shows a number of questions that deal with the geometric accuracy of a 3D building. The questions are part of the overall question whether the building model is usable for a certain application.

For an absolute accuracy measure, an independent reference dataset would be needed in order to check for differences between the reconstructed models and the reference dataset. These differences contain information on the mean and local variation in 3D between reference data set and reconstructed model. Reference data can be acquired manually or semi-automatic, as in (Rottensteiner, 2006). If the reference data is considered to be the ground truth, its quality should be better than the reconstructed models. The problem is that such a detailed reference dataset might not be available (yet) at a large scale for detailed models as in Figure 1. When using reference data to determine the quality of a certain set of reconstructed buildings, it is necessary to correctly analyse differences between the two datasets.

Suppose the building from Figure 1 has been constructed using an airborne laser data set. The top ridges have been determined by intersection of two roof faces, which are accurately described by a plane through planar segments. The top ridges in Figure 1 can be determined with a higher accuracy than the gutter of the same building. This information is essential when analysing differences between the model and reference data of either the ridges or the gutters.

Before checking on reference data, we can predict the quality of the reconstructed models using internal quality measures. These quality measures can be calculated from the input data, and can therefore not be seen as independent. However, it is a measure for the expected quality. The advantages are that the quality can be predicted for the complete dataset and that it provides information on which object parts are less accurate than others. When such a quality description is directly attached to the reconstructed building models, it will be possible to perform a stochastically correct quality check using reference data once available. Especially in the phase of creating city models, instead of updating these models, it is important to describe the expected quality using internal measures.

The following study presents criteria to evaluate the quality of reconstructed building models. We present indicators from a reconstruction point of view, answering the question what can be expected from the data and processing steps. These evaluation criteria are indicative measures for the quality of the models. The evaluation parameters do not exactly depend on a specific reconstruction method. However, the assumption is that the models are derived from dense airborne laser scanner data.

Our goal is to better describe the expectation of the quality of 3D buildings, derived from dense airborne laser scanner data. For end users as well as for researchers it is of interest to have insight in the construction/structure of the quality, in order to improve the 3D model or decide if the model is suitable for a certain application.

2. RELATED WORK

Kaartinen et al. (2005) present a comparison of 11 image and/or laser scanning based building reconstruction techniques. Reconstructed buildings have been compared to reference data. Quality performance was based on parameters such as ridge length, building outlines and roof inclination. Major conclusions on laser scanning based approaches were that the roof inclinations and ridges can be determined accurately, whereas the outlines of the buildings can better be determined by image based techniques. Rottensteiner (2006) describes the use of aerial images for the creation of reference data in order to determine the quality of laser scanner based reconstructed buildings. It was found that the planimetric accuracy is in the order of point spacing and the height accuracy is about 10-20 cm. Weaker parts were found at step edges that were located in a relatively coarse part of the dataset. Both the conclusions in (Kaartinen et al., 2005) and (Rottensteiner, 2006) can actually be seen as a confirmation of the expectations, looking at the input data and the reconstruction techniques.

Dorninger and Pfeifer (2008) present a building reconstruction approach that includes an absolute and relative quality description for the reconstructed buildings. They used an independent reference data set to analyse difference on several parameters, such as eave height and area of the buildings. Next to that, the authors calculate the orthogonal difference between the original point cloud and the reconstructed models. This gives a quantitative and visual impression of part of the correctness of the model. Other evaluation criteria mentioned in that study are the checking if all segments are represented by a closed polygon and whether the area of these segments is comparable with the area of the corresponding roof polygon.

In this paper the focus is on understanding the quality of 3D buildings derived from airborne laser scanning data. We present several methods that refine the expectations of the quality of the reconstructed buildings. Once the understanding is clear, the scientist knows where the weak elements are and the user can better determine if the models are suitable for his application.

3. EXPECTED QUALITY OF EXTRACTED FEATURES FROM LASER DATA

Features found in the data are results of a chain of stochastic processes and deterministic assumptions. This makes the exact position and even the existence of a feature uncertain.

3.1 Quality of input laser data

Starting point for a relative quality measure is to determine the quality of the input data, in our study airborne laser scanner data. Generally, in such a data set systematic and stochastic errors occur, depending on the configuration during the time of acquisition. Several studies described methods to detect and eliminate some of the systematic errors by analysing objects in strip overlapping areas (Crombaghs et al., 2002; Pfeifer et al., 2005; Vosselman, 2008). Reference data might be incorporated in this step, e.g. in a calibration or overall strip adjustment procedure, to achieve an absolute quality measure for the input data. Typical values for the planimetric accuracy of dense airborne laser scanner data are 15-25 cm standard deviation (Rentsch and Krzystek, 2009) and (Vosselman and Maas, 2001), and 5-10 cm for the vertical accuracy (Crombaghs et al., 2002).

The quality of the input dataset propagates to the extracted features in a systematic manner: if the whole laser data contains a certain offset, the extracted features inherit the same offset. Once the quality of the input data is known, it is of interest to analyse the quality of the features extracted from that data. In this section we analyse planar segments, intersection lines and corner points. However we start with analysing the absence of laser data.

3.2 Absence of laser data

The absence of laser data is an important indication that not all objects are completely captured by the data. This means that the reconstructed models might not be complete. The absence of data often occurs at flat roof faces that are covered by a thin layer of water, amongst others on top of dormers. The area shown in Figure 2 contains many data gaps due to flat roof parts at dormers. Detection of these gaps is an important measure for the incompleteness of the final model.

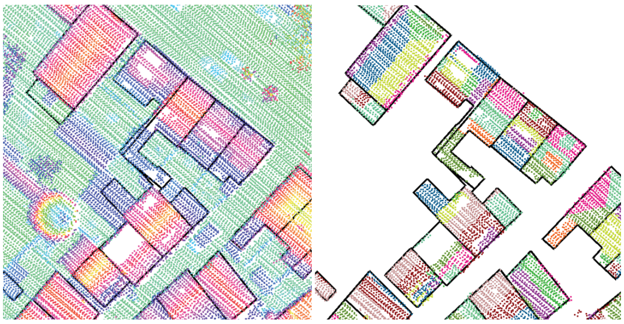

Figure 2 Color coded laser points overlaid on a topographic map. Some flat roof parts are not captured in the data (left). Result of segmentation of data inside map polygons (right).

The quality measure that can be attached to the output is the area per building that contains no laser points, if this area exceeds a certain threshold.

3.3 Planar segments

Finding planar segments for roof extraction is widely used in building reconstruction algorithms, (Brenner, 2000; Dorninger and Pfeifer, 2008; Hofmann, 2004; Jochem et al., 2009; Rottensteiner and Briese, 2003; Vosselman and Dijkman, 2001). As described in section 3.2 one of the problems is that some roof faces might not be captured at all in the laser data, let alone detected in the segments. If a planar segment is found, the question is whether the roof face is actually planar. At this point the level of detail plays a role to define the generalisation level between real world and the desired 3D model. Suppose the area only consists of planar roof faces then the quality of the plane parameters of the segment increases with the size and planarity of the segment. Finding such segments cannot be considered as a research problem anymore. The problems arise if every segment is considered to represent one roof face, every roof face is considered to be represented by one segment and the outline of the segment is seen as the outline of the roof. Especially for steep, dark, flat and wet roof faces, these assumptions are likely to fail as the bounds of these segments, if detected at all, are rather noisy due to reflected or absorbed laser pulses.

3.4 Roof edges

In Figure 3 a schematic overview is presented of varying quality of edges and corner points, caused by the various ways how they are realised. A simple half hip roof, including a dormer and a flat shed attached to the building is shown. The figure is not supposed to be representative for all building reconstruction approaches, but it is an example to show the varying quality within one building.

In this paragraph several roof edges are discussed that differ in terms of determination. The first type is the edge represented by an intersection line between two roof faces, in Figure 3 shown as green lines. The pose is determined by the intersection of two planes. The quality of the pose depends on the size of each of the two roof faces and the intersection angle between the two faces. That is the reason that intersection lines of gable and hip type roofs are generally better determined than the lower intersection lines at gambrel or mansard roofs.

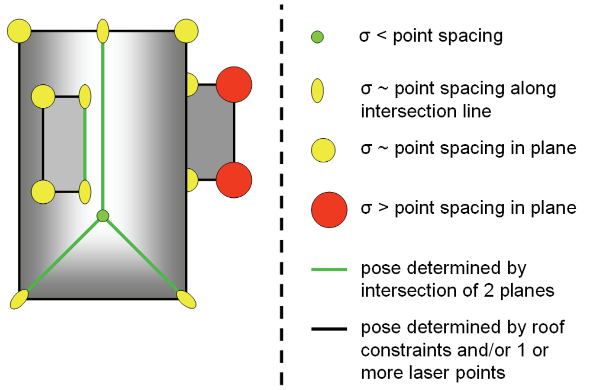

Figure 3 Quality differences in roof edges and corner points.

Second type of roof edges are the outer boundaries of roof faces. Examples are the roof gutter locations. Typical rules of thumb for the quality of these edge locations are in the order of point spacing (Rottensteiner, 2006) and (Kaartinen et al., 2005). Some approaches take the location of a map polygon for these roof edge locations, such as (Vosselman and Dijkman, 2001) and (Kada and McKinley, 2009). If the map polygon represents the outer boundary of the roofs, i.e. not the walls, in an accurate manner this can be used to improve the accuracy and reliability of the outer edges.

3.5 Corner points

The position of the end point along the 3D line depends on the existence of nearby laser points in both segments. We assume that the geometric quality of the end points of intersection lines between two segments is in the order of the median point spacing along the intersection line. If this line again is intersected by a third segment the quality significantly improves, as the position is determined by the intersection of three planes. In Figure 3 one object point is determined by the intersection of three roof planes, and can be considered to be accurately determined. Next, there are five points well determined in a single direction, as they are at the end point of an intersection line. These are visualised by ellipses. Other points are considered to lie in a certain roof plane, but the exact location depends on the point spacing and the strength of constraints. Two points got a large precision value, visualised by red circles, as they depend on the location of laser points on a flat surface. As the borders of flat segments are likely to suffer from lack of points due to water standing on that roof part, the position can be considered as most uncertain of this example.

3.6 Height jumps

In Figure 4 two types of height jumps are shown. The top figure shows a height jump between one tilted and one flat roof part. The bottom part of the figure shows a height jump between two flat roof faces.

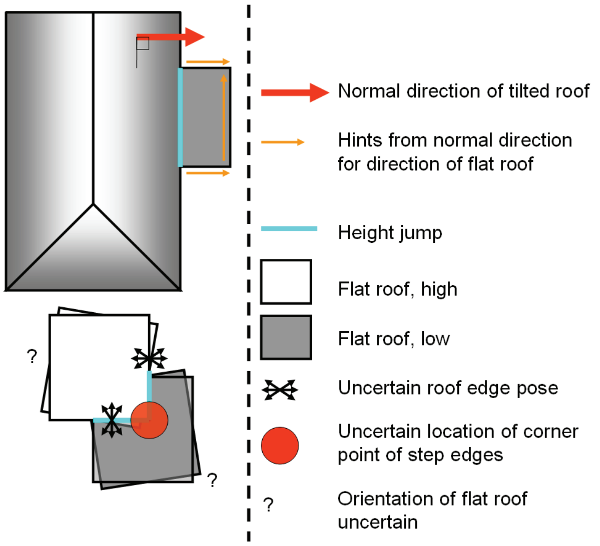

Figure 4 Two types of height jumps: between a tilted roof and a flat roof (top) and between two flat roofs (bottom).

It is expected that the latter situation results in less reliable reconstructed roof edges. The reason is twofold:

1. The lower boundary of the tilted roof, e.g. the gutter, gives an approximate location for the step edge. The gutter location can be determined by observations, e.g. lowest laser point in that roof segment or the end of a tilted intersection line, and geometric constraints.
2. Next, it is shown that if there is a height jump between a tilted roof and a flat roof, the normal of the tilted roof can be helpful to limit the directions of the flat roof, although it is likely that the precision will still be larger than the point spacing because of the earlier mentioned lack of points on flat segments. When step edges occur between two flat roof faces, the normal of the planes do not contain information for the direction of the step edge and the outlines of both roof faces.

Depending on the reconstruction algorithm, other data sources, such as images or maps, can be incorporated to improve the location of edges or points in the model. Especially algorithms using detailed map or image information to hypothesize locations for the outer (flat) roof boundaries can expect improvements in the accuracy of these edges and corner points.

3.7 The effect of constraints to 3D models

Geometric constraints can be introduced in many ways, varying from regularities between two planes or neighbouring vertices on edges (Rottensteiner, 2006), modelling weak CSG primitives (Brenner, 2004) to ensure topological and geometrical consistency, or using a fully model driven approach enforcing strong constraints to the models, such as the model driven approach presented in (Kada and McKinley, 2009; Maas and Vosselman, 1999). The effect of constraints to the quality of the models has been reported as positive, e.g. an improvement of 5-45% in (Rottensteiner, 2006). Constraints can be seen as additional observations to data features in order to be of added value to solve the parameters of the 3D model. Geometric improvements are only possible if the constraints are correctly tuned to the data.

4. QUALITY MEASURES TO IMPROVE PROCESSING

In the previous section a list of influences of the quality of extracted data features have been shown. In this section results are shown of possible implementations using a dense airborne laser data set of about 20 points per m^2. The message of this section is to show that the quality measures can be used to detect complex situations, adapt processing parameters and adapt assumptions or regulations. During the segmentation stage, differences between individual laser points and a plane through the segments can be stored. In surface growing algorithms this difference is used to check if the point might belong to the growing segment. If systematic patterns are found when analysing these differences, segmentation parameters might be adjusted in order to avoid under or over segmentation. Analysing the systematic pattern of large residuals has earlier been used in (Filin et al., 2007) for the detection of curved roof faces.

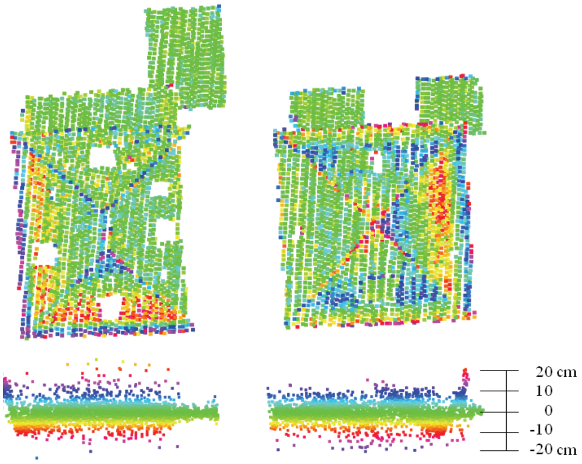

Figure 5 Orthogonal differences between individual laser points and a plane through the corresponding segment. Large residuals are colored blue and red.

In Figure 5 the systematic patterns in the differences called the attention to a subtle angle difference in all roof faces what seemed to be a simple hip roof (left) and a simple pyramid roof (right). Detection of these situations is of great interest as the segmentation parameter values might just be at the limit of the real world situation.

Situations that are at the edge of threshold values, can cause problems in the segmentation results, as for some situations two roof parts are found as for other parts only one segment is found. This is shown in Figure 6 where every roof side actually consists of two parts: a higher part and a lower part. Two roofs are correctly represented by two segments, whereas six others contain only one segment. Additional problem here is that the lower roof segments are partly located at overhanging roof parts. In this reconstruction approach a topographic map has been used to select the roof segments, leaving out one large segment.

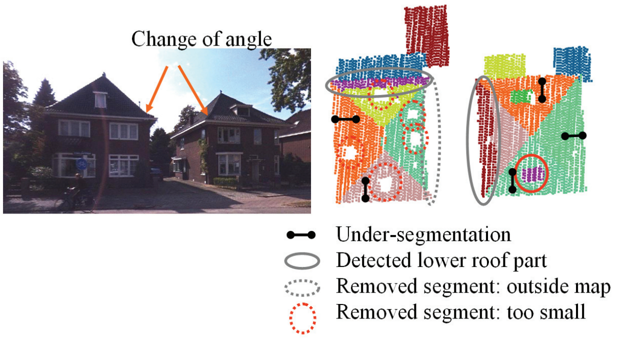

Figure 6 Segmentation results at complex situations.

The advantage of the having the relation between data and model is that we can check if individual model faces fit to the data. One of the quality checks is the perpendicular distance between 3D model faces and laser points, similar to the approach presented in (Dorninger and Pfeifer, 2008). Discrepancies between data and model can be visualised and quantified easily. Figure 7 shows the distance between laser points and its roof faces reconstructed by a model driven reconstruction approach, coloured in intervals [green < 20 cm], [20 cm < yellow < 50 cm] and [red > 50cm].

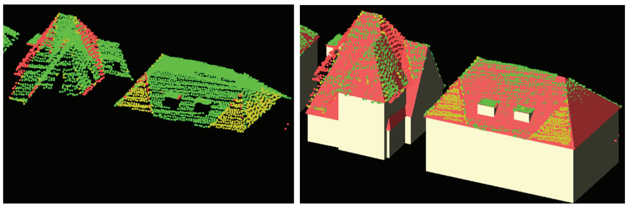

Figure 7 Orthogonal distances between laser points and 3D model (left), overlaid on the 3D model (right).

It is expected that in data driven approaches the majority of residuals is small and even the average residual is (nearly) zero as the model faces are constructed by fitting a plane through the same laser points. Obviously, large residuals are found on laser points or even complete segments that are left out from the reconstruction step. In model driven approaches, this quality check is helpful to see whether the data fits to each roof face, or that there are asymmetric shapes in the terrain that are incorrectly modelled by a symmetric model driven shape. In Figure 8an example is shown of a symmetric reconstructed hip roof and its discrepancies to the laser data. The residuals clearly show a systematic pattern. This systematic pattern can automatically be detected by selecting the segments that have a large number of points with large residuals. Buildings containing these segments can either be shown to the users for manual interpretation or can serve as input for an alternative reconstruction approach. The latter was the case in Figure 8 where constraints on the roof inclination were changed from ‘equal for all hip roof faces’ (top row) to ‘equal for two opposite roof faces’ (bottom row).

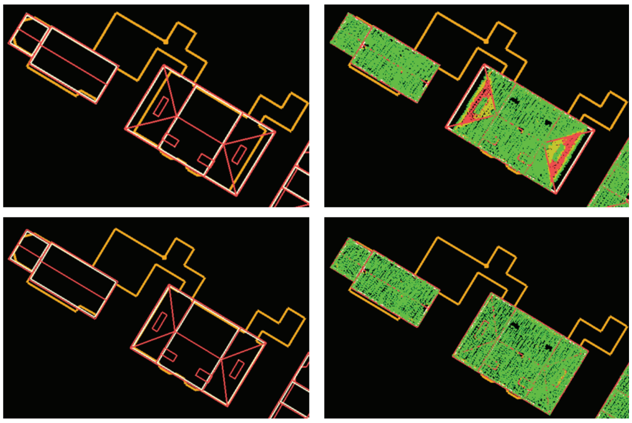

Figure 8 Top row: hip roof reconstructed with equal inclination angles. Right: laser point residuals superimposed. Bottom row: hip roof reconstructed with two different inclination angles. Right: as a result, the improvement on the laser point residuals is directly visible. Map polygon is shown as yellow polygon.

The disadvantage of calculating the perpendicular distance between laser points and model faces is that it can be misleading in the sense that most of the laser points show a small residual. This is especially the case for data driven approaches that fit each individual roof face through a roof segment. It does not show the quality of the location of the edges of the roofs. Another quality measure is given by calculating the distance between 3D corner points and the nearest laser point, as visualised in Figure 9. Although this is not an independent check either, it is of added value to the previous height check, because it holds information on how assumptions and constraints on the edge locations fit to the data.

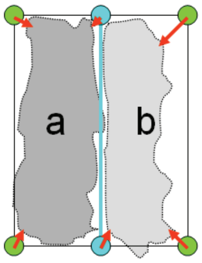

Figure 9 The distance between a model point and nearest laser point (indicated by red arrows) as a quality measure.

In Figure 10 two situations are shown in grey circles, where the corner points of building models have a large distance to the nearest laser point. A gable roof, which is reconstructed using a model driven approach, is shown in the front part of the scene. The constraint that the gable roof is symmetric is a basic assumption from the model driven approach. However, using the distance to the nearest laser point in the corresponding roof segment, it is detected that one gutter has incorrectly been reconstructed. Rejecting the symmetric constraint is the solution for this case. The other situation shows a dormer which corner points do not have nearby laser points. This often occurs at situations where water is standing in a corner of dormer. In this case, the model is correct; however the quality measure indicates a high value. Knowledge on the expectation of the quality of the model at this point as explained in section 3, helps interpreting and accepting the larger distance between data and model.

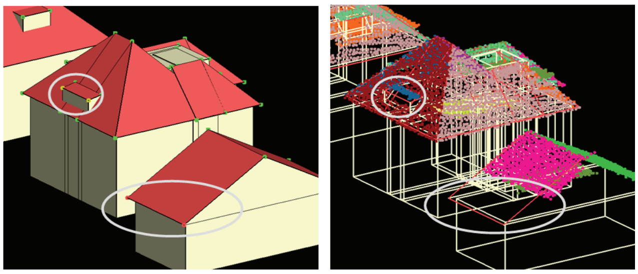

Figure 10 Nearest distance between 3D model points and laser points, coloured by residual value (<20 cm is green, <50 cm is yellow, > 50 cm is red). Right: Roof laser segments projected on wireframe.

Complete segments that have not been used for building reconstruction are also mentioned in (Oude Elberink and Vosselman, 2009) where the reasons were discussed. The recording of these segments is enough to have a quality measure of the reconstructed buildings, as it directly contains information on the completeness of the reconstructed buildings.

5. QUALITY MEASURES AS OUTPUT ATTACHED TO 3D MODELS

So far, situations have been shown that show a probable cause of which some have a relative simple solution. These solutions can be implemented such that the best alternative is chosen automatically for each of the situations. In practice however, it is still advisable to deliver these quality measures together with the reconstructed model. Future users can then indicate if the model is suitable for certain applications.

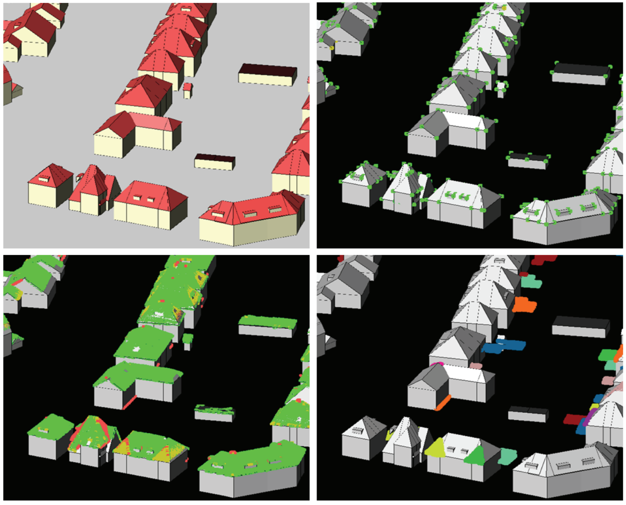

Figure 11 Reconstructed model (upper left) is only part of the output; nearest distance between corner points and laser points (upper right), orthogonal distance between laser points and roof face (lower left) and segments not used by the reconstruction algorithm (lower right).

An example is shown in Figure 11 where the reconstructed model (upper left) is only part of the output of the building reconstruction algorithm, as three quality measures are attached to the model: nearest distance between corner points and laser points (upper right), orthogonal distance between laser points and corresponding roof faces (lower left) and the segments that have not been used for the reconstruction (lower right).

6. CONCLUSIONS AND FUTURE WORK

As the 3D models become more detailed, it is of importance to correctly judge the quality of these models. The quality of reconstructed buildings can not be described in one parameter. We have shown that the quality of features depends on how they are constructed. Using that knowledge, one can predict what the quality of features in the end product is. This is useful to see where the weak parts are in the reconstruction method or in the end product even if there is no appropriate reference data available. The use of quality measures to automatically improve or adjust the processing parameters remains a challenging task as the existence of large residuals might have multiple causes. Future work is setting up an appropriate system of equations to handle differences between reference data and 3D model data.

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