Modeling of 3D buildings by using Airborne Laser Scanning data and map data

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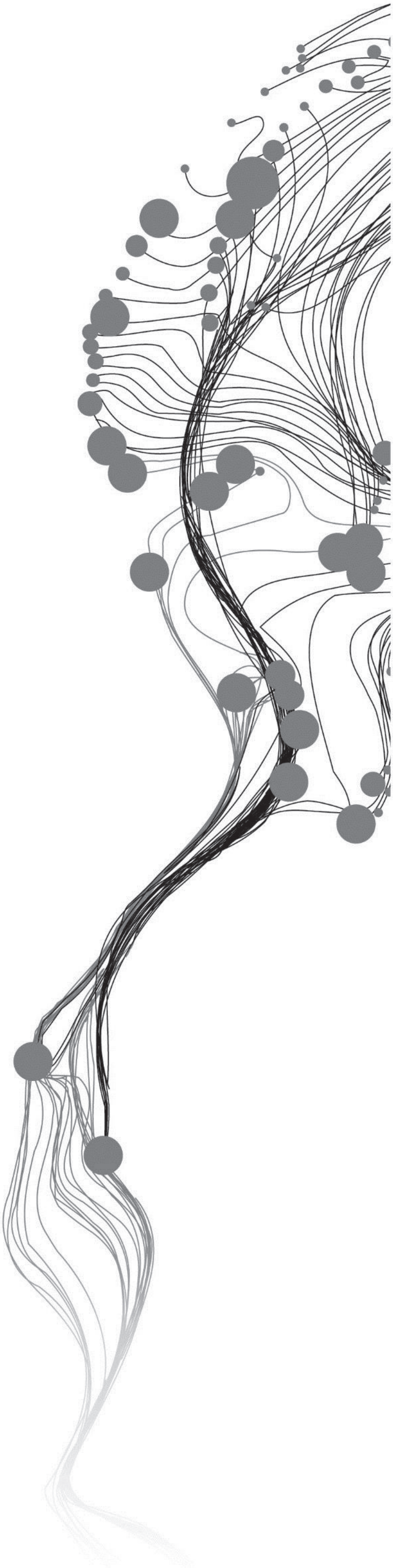

MODELING OF 3D BUILDINGS BY USING AIRBORNE LASER SCANNING DATA AND MAP DATA

QINGYANG LI
Enschede, The Netherlands, February, 2014

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Having been introduced into the fields of survey and engineering industry for decades, airborne laser scanning technology is becoming maturer and widely spread. As one of its most significant products, 3D city models are popular among city planners and citizens. Plenty methods of how to automatically generate 3D building models from point clouds were proposed these years.

This research describes a method for building reconstruction from ALS data and cadastral maps. The map data is used as a hard constraint in this method which helps to create the walls and estimate the boundaries of roofs. Then the properties of topology graphs are taken advantages of detecting roof shapes. Relations among adjacent faces and intersection lines are explicitly indicated by corresponding topology graphs. As a result, the roof shapes are revealed by calculated roof skeletons. In the next phrase of the proposed algorithm, a knowledge-based optimization is developed for intersection lines placement. Three types of candidate corners are defined for the assignment of intersection lines to map outlines. By determining the nearest weighted possible location and applying geometrical regularism to two endpoints, each intersection line is adjusted to a preferable place. The roof planes are following detected and created with corresponding laser data, structure lines and map line segments. At last, the final 3D models are reconstructed by heights assignment and adding walls.

The evaluation of 3D models is conducted in both 2D roof shapes and 3D environment. The results of the evaluation showed that the proposed method works well for building reconstruction since all the test data were result in final output models. Besides, the residual of most roof points were less than 10 centimetres. Finally, the proposed method was discussed for improvement and some recommendations were given for further research.

Keywords:
Building modelling, roof detection, topology graph, roof skeleton optimization

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Thank you for my family members who always support me.
Thank you for my fellows who always stand by my side.
Thank you for my supervisor Sander and adviser Biao for helping in this research.
Thank you for my friends that are around the world.
Thank you for my life to have this experience.
Unforgettable…

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1. INTRODUCTION

1.1. Motivation

The demand of 3D city models is growing rapidly in recent years. As virtual environment of real world can bring users more intuitive and real experience, 3D city models have become increasingly popular among various types of utilizers. Through analysing problems and making decisions in the three dimension world, the techniques and products can better contribute to management and application in different fields, such as urban planning, telecommunication industry and post-disaster reconstruction.

Compared with traditional aerial image-based modelling technique, airborne laser scanning is more efficiency and promising in 3D city modelling. High accuracy and density of point clouds, including height data, can make the extraction of features much easier and more reliable. Besides, the increasing utilization of laser scanning technique is also motivated by the difficulties in recognizing very complex buildings and required semi-automatic procedure of aerial image interpretation which lead to time-consuming and a lot of manual works (Haala et al., 2010).

Plenty of researchers have proposed highly automatic method and algorithms to generate 3D buildings based on point clouds. While building orientations, heights and slopes of planar roof faces can be accurately estimated from the data, the roof outlines as well as building footprints are more difficult to determine(Vosselman et al., 2001). The improvement of modelling this part can benefit from using city ground plan or 2D digital map data which is now available in national geographical information system (GIS).

The digitized topographic map or ground plan has several advantages in building reconstruction and different usages have been applied in 3D city modelling:

a) They can give precise locations of building walls and some roof edges can be reconstructed by intersecting vertical walls with detected roof faces (Vosselman & Dijkman, 2001). The outlines of buildings can also help to reduce costs of building detection process (Haala et al., 1998).
b) The constraints of roof face orientations can be defined and calculated from map data (Schwalbe et al., 2005).
c) The decomposition of building outlines is the mainly usage of the map data as they can indicate the composition of complex buildings. When modelling buildings, the ground plan is partitioned into polygons and each of them will be matched to a certain primitive, then 3D models can be reconstructed by combining those primitives. Besides, the decomposition lines may give hints of interior walls which are occluded by the overhang roofs.
d) Topographic map can provide reliable 2D semantics information and neighbourhood relations (S. J. Oude Elberink, 2010).

1.2. Problem statement

Although the results of many researches have proved that map data works well with ALS data for reconstructing 3D city models, some problems still exist. One of the drawbacks is that when ground plan is simply used for detecting buildings and filtering the outliers (Overby et al., 2004; Rau et al., 2011), inconsistency may occur between detected roof faces and ground plan due to the overhanging parts of the roofs or map data which is not up to date.

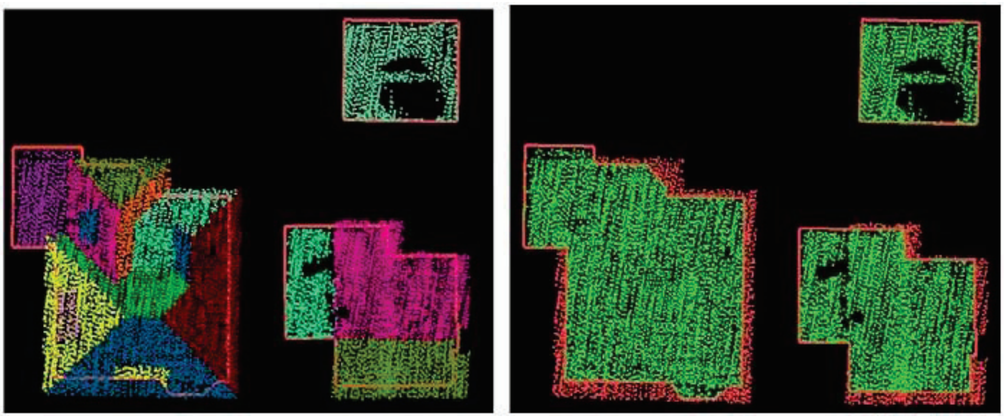


Figure 1-1 Inconsistency problem due to roof overhangs (S. J. Oude Elberink, 2010)

Second problems mainly come from the usage of building decomposition by ground plan. Normally, ground plan is partitioned into polygons by extended edges and concave corners. The results of decomposition can be various and lead to large amount of computation. Many details may also get lost as small segments are always ignored or generalized. Besides, inconsistency and mismatching may exist when merging adjacent primitives into whole buildings.

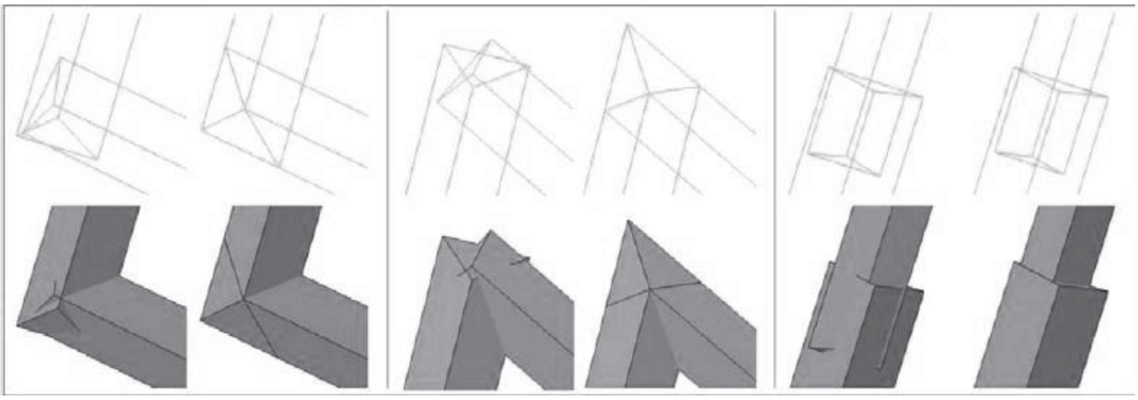


Figure 1-2: Mismatching problem when merging adjacent primitives(Huang et al., 2013)

The third problem arises because of the inconsistency between ground plan and structure lines which are derived from the point clouds data. The detected intersection lines and step-edges are inaccurate and even missing due to inhomogeneous point density. Meanwhile, structure lines are sometimes not corresponding to the ground plan as they are not parallel to edges or they do not exactly intersect with building outlines at the corners (Van Winden, 2012).

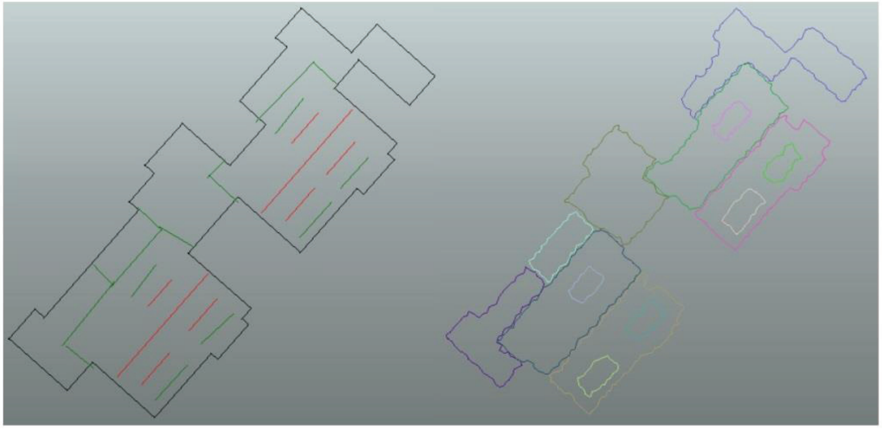


Figure 1-3 Inconsistency between structure lines and map data (Van Winden, 2012)

According to above statement, the main problem is that the 3D features extracted from point clouds do not obey topology and geometry regulations and also not fit well with 2D ground plan. Thus potential improvements are necessary to be made for optimizing the configuration of obtained features and minimizing the inconsistency while reconstruct buildings. In this context, roof topology graphs and constraints such as "weak primitives"(Brenner, 2004) will be studied. Both hard and soft constraints are going to be defined and implemented for the optimization. Besides, a highly automatic workflow of building reconstruction will be provided to fulfil those constraints and minimize the inconsistency.

1.3. Research identification

1.3.1. Research objectives

The main objective of this research is to propose an automatic workflow for building reconstruction; both hard and soft constraints are defined to combine extracted 3D roofs structure with 2D map data. The general goal is narrowed into following objectives:

- To combine 3D roof surfaces with 2D map outlines to a logical and visually attractive 3D building model.
- To take advantage of topology graphs for roof structure detection and reconstruction.
- To define hard and soft constraints for extracted roof features, such as intersection lines, height jump lines.
- To design and implement an optimization algorithm that can find a better solution of line configuration and make the inconsistency minimum.

1.3.2. Research questions

In order to achieve the sub-objectives above, several questions are going to be discussed and answered during the research:

- How to deal with inconsistency between extracted features and ground plan?
- What information can be indicated from roof topology graphs?
- How to derive roof structures using the properties of topology graphs?
- How to define and formulate well-structured hard and soft constraints for roof features?
- Which optimization algorithm is going to be used in my situation?
- How to implement the optimization algorithm with experiment data?
- How to evaluate the performance of proposed workflow and algorithm using the experiment data?

1.3.3. Innovation aimed at

As there is always inconsistency between obtained features from point cloud data and ground plans, the novelty of my work will focus on the optimization of building reconstruction by a set of constraints. Complete hard and soft constraints are going to be defined and an optimization algorithm for building reconstruction is proposed to configure extracted primitives under those constraints.

1.4. Thesis structure

The thesis is organised into six chapters. Motivation of this research and problems of previous works are already stated in first chapter as well as research objectives and questions. Chapter 2 starts with a brief introduction of airborne laser scanning technique and review the state of art of building reconstruction methods using ALS data. In Chapter 3, the methodology is displayed after studying the properties of roof topology graphs and an optimization algorithm is designed for structure lines configuration. Chapter 4 describes the implementation and results of proposed method while Chapter 5 evaluates the final results and discusses the performance of the algorithm. Finally, conclusions are drawn and recommendations are made for further research in the Chapter 6.

2. LITERATURE REVIEW

2.1. Brief introduction of Airbonre laser scanning

Airborne laser scanning (ALS) technique now is widely used for generating high quality 3D topography, including buildings, roads; vegetation and etc. (see Figure 2-1). The work is done either from an aircraft of a helicopter with a laser scanner system. The range between the flight and objective can be achieved by illuminating laser from the scanner. Beside the laser scanner system, global positioning system (GPS) and inertial navigation system (INS) are integrated into the on-board systems to measure the horizontal location and orientation of the flight. A GPS ground station is also significant for the measurement because it can compensate atmosphere effects and improve the accuracy by differential GPS (DGPS)(*Airborne and Terrestrial Laser Scanning*, 2010).

Figure 2-1 Airborne laser scanning at working

Compared with traditional remote sensing techniques which also generate elevation information, ALS has its own advantages and disadvantages. One considerable characteristic is that the active laser systems are independent of sunlight which makes the survey can be conducted at both daytime and night. Besides, high point density (about 30 points/m^2) and high accurate data can acquired in a relatively short time. Although disadvantages still exist thanks to low reflection of water surface or shelter from dense vegetation, airborne laser scanning is still a considerable way for large area survey.
The measurement data of laser scanning are unstructured 3D points which also calls point clouds. Other information such as multiple echoes and full-waveform are also recorded. All these information are playing important roles in classification, segmentation and other data processing and applications.

2.2. Building reconstruction from ALS data

Many researches have been done about 3D building modelling using Airborne Laser Scanning data for the past decades. Typically, there are two approaches for building reconstruction: data-driven and model-driven. Here below are some related works of building reconstruction using airborne laser data.
In the early stage, the ground plan was already introduced in building reconstruction. They were partitioned into small polygons by utilizing edges and concave corners for detecting roof shapes of each partition. For example, (Haala et al., 1998) decomposed the ground plan into regular rectangular and utilized DSM for determining the normal vectors of roof faces. Four simple primitives were pre-defined in their situation and each building was represented by a combination of basic primitives.

(Vosselman & Dijkman, 2001) proposed both two different strategies for reconstruction of building models based on the two different approaches. First of all, ground plan was partitioned into a set of polygons by extending concave ground plan corners and a better roof detection can be done by 3D Hough transformation. In the first strategy, the intersection lines and height jump lines were detected from obtained roofs for the refinement of ground plan. The second strategy used coarse initial models and refined by remained point segments. The results of two method showed that the second strategy was better as more buildings and more details of those buildings were reconstructed.

A review work of model-driven and data-driven approaches have been done by (Tarsha-Kurdi et al., 2007). The authors analysed and compared the two approaches: the model-driven approach require a searching process from pre-defined primitive library and calculation for the most probable parameters while the data-driven approach can model unspecified building without relating it to a set of parameters; the model-driven approach can provide a very fast way for modelling without deformations in the final results while data-driven approach can obtain more reliable polyhedral model with deformations and more processing time.

(Kada et al., 2009) proposed a cell decomposition algorithm to divide the ground plan into irregular polygons by the edges of outlines. A model-driven approach was then taken advantage of for building reconstruction, and the roof structure was determined by calculation of normal vectors and compared with five basic shapes. The result of their work showed good city models of specific areas.

A similar work has been done by (Lafarge et al., 2008). Instead of ALS data and map data as input, the authors used DEM. The building outlines were firstly extracted from DEM and then estimated by a set of quadrilaterals interactively or automatically. Then pre-defined 3D blocks were places on the 2D sections. Finally, a Bayesian algorithm helped to find the optimal configuration of 3D blocks using a RJMCMC process.

A bottom-up approach was proposed by (Van Winden, 2012) which used intersection lines and step edges for ground plan partitioning. Then 2D roof surfaces were created by node configuration of four possible connections. At last, LoD2 solid objects were modelled by converting 2D surfaces back to three dimensions as well as vertical balconies and walls were added.

2.3. Topology graphs

Topology graphs represent the topological relations between roof segments. They had been used in many graph-matching algorithms.

(Verma et al., 2006) used a region adjacency graph for roof structure determination. Firstly, point clouds of buildings were obtained by principal component analysis and connected component analysis. Then each complete roof was divided by planar segmentation and roof topology graph was achieved. Next step, pre-defined primitives were used to compare with sub-graphs of each roof topology graph and roof types can be determined (see Figure 2-2). Finally, building models were reconstructed by a least square estimation with additional constraints.

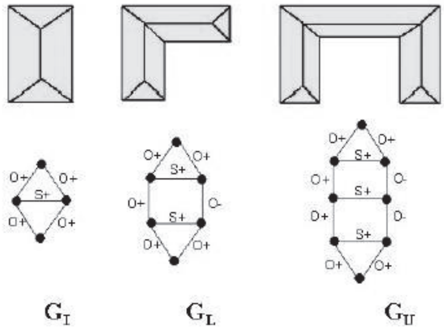


Figure 2-2 Roof topology graphs with corresponding simple parametric shapes(Verma et al., 2006)

In the work of (S. J. Oude Elberink, 2010), the point clouds were segmented and structure lines such as intersection lines and step-edges were detected at first. Then roof topology graphs were set up for target based graph matching algorithm and different roof structures were detected. Two approaches for building reconstruction were applied later. One is data-driven approach for complete match results. Map data were integrated and building ground plans were decomposed by those structure lines. Next, each roof face was detected by assigning those structure lines to building outlines. Finally, the walls were reconstructed from map outlines and the buildings were modelled by reconstructed roof faces and walls. Second approach was more like a model-drive method. Matched models from target based matching algorithm were reconstructed using parameterised models, and for each model, flexible constraints were applied to related features.

2.4. Summary

Having been utilized in the field of building reconstruction for decades, airborne laser scanning are already proved to be an efficient technique for 3D modelling. The above reviews presented some proposed methods for building reconstruction and described the principles of how they work respectively. Among them, roof topology graphs were turned out to be a good choice for roof shape detection and reconstruction. In this paper, roof topology graphs are also used for those purposes but instead of graph matching method, this research will take advantages of the hidden information from roof topology graphs. Detailed analysis and methodology of this research will be illustrated in next chapter.

3. METHODOLOGY AND ANALYSIS

3.1. Introduction

In this chapter, the methodology and workflow which aim to achieve above objectives are described. After a demonstration of the framework, the properties of roof topology graph are analysed and its usages in the methodology are given. Next, three sub-sections of the algorithm are presented respectively, following by a brief introduction of the strategy of evaluation.

3.2. Framework of the methodology

Since this is an experimental research, the methodology is developed based on repeated trials and tests. By studying topology graphs, the method for roof shape detection is proposed. Then through observation and statistics analysis of experimental data, the algorithm for roof structure optimization is come up with. Afterwards, all roof faces of each building are determined with different heights assigned to structure nodes. At last, the evaluation strategy of this research is developed and applied to final results. The general framework is depicted as Figure 3-1.

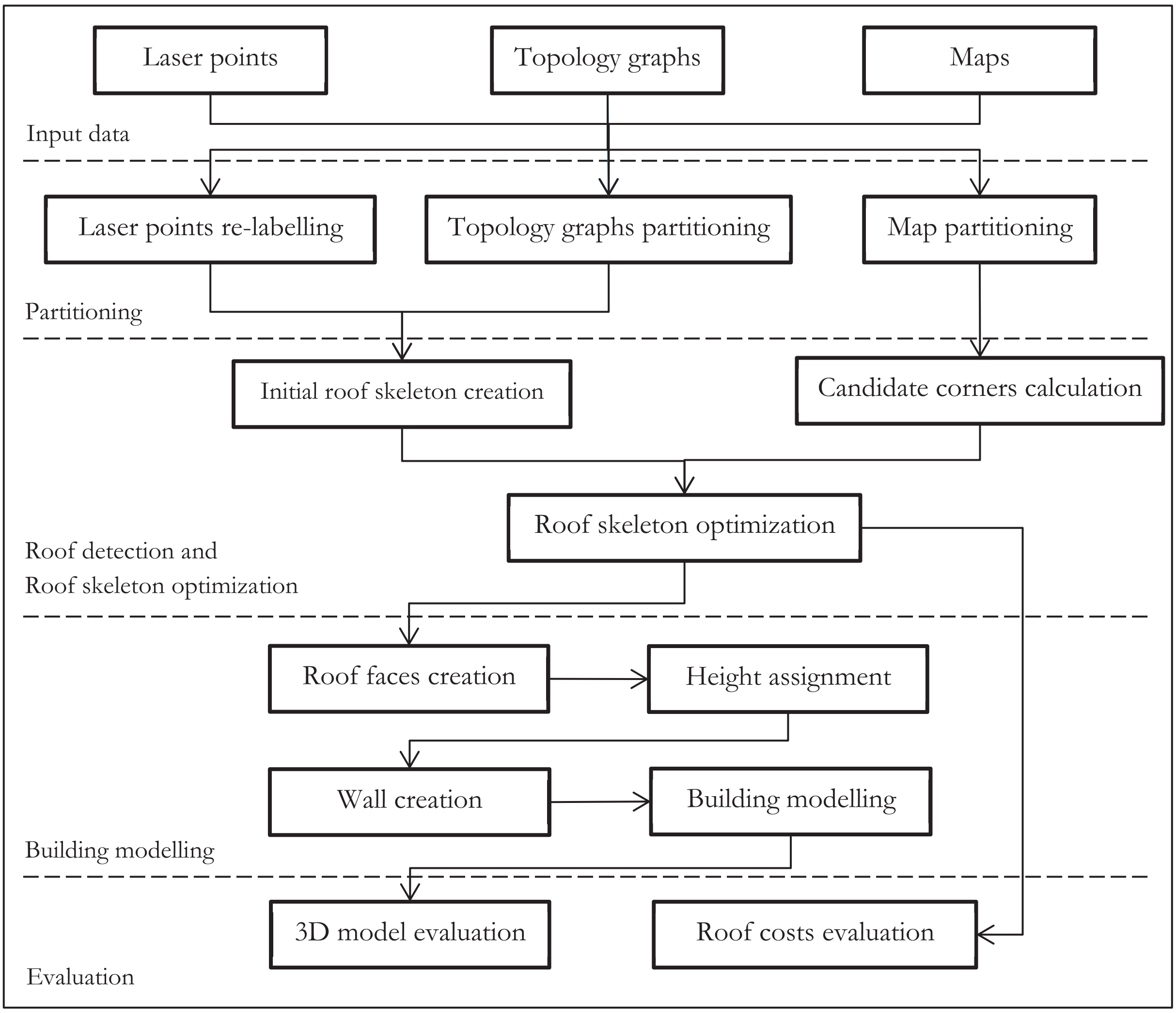


Figure 3-1 Framework of the methodology

3.3. Topology graphs

Topology graphs represent the topological relations between roof segments. Each node in the graphs is a roof segment while each edge means the intersection line or step edge of two adjacent roof segments. Unlike geometry shapes may have problems in representing roof structures with disconnected intersection lines; topology graphs can indicate constraints for both roof segments and structure lines between them. An example of topology graph and corresponding structure lines are given in Figure 3-2.

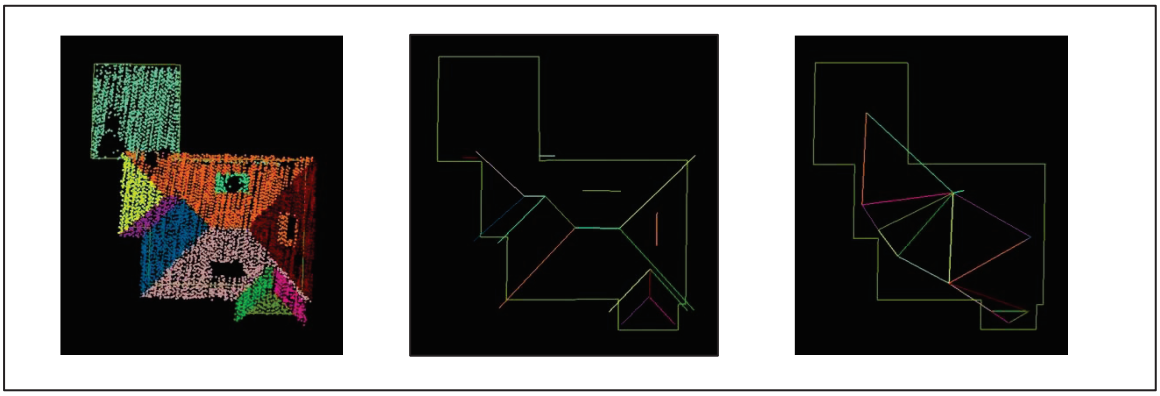


Figure 3-2 Roof segments (left), structure lines (middle) and roof topology graph (right)

Through analysing the properties and structures of topology graphs and corresponding roof structure lines, four topological constrains are developed and utilized in the research:

Firstly, Topology graphs can directly display the relations between roof segments, as it is the definition of topology graphs. From well-labelled topology graphs, we can easily find the intersect line with its related roof segments. This constraint will contribute to creating each roof face with corresponding structure lines and roof outlines. Its detailed realization in the research is presented in later chapter. Besides, this feature may also help for re-calculation of intersection lines if topology graphs have been corrected.

Secondly, topology graphs also imply the relations between intersection lines. In Figure 3-3, for each quadrangle or triangle in the topology graphs, it indicates an internal corner which refers to the intersect point of relevant structure lines. Such quadrangle or triangle is called a circle in the topology graphs. This property can avoid the potential intersection problem in geometrical situation but also indicate correct topological relations among intersection lines.

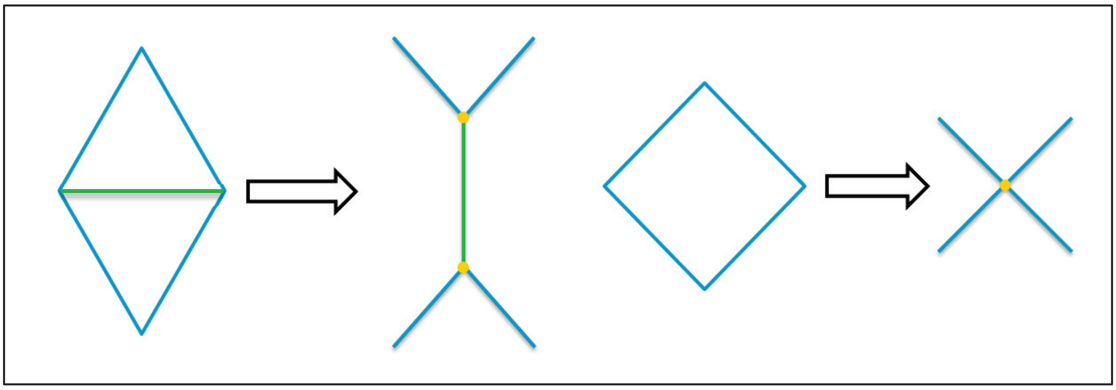


Figure 3-3 the quadrangle or triangle shape in topology graphs.
The internal corners (yellow) are shown in structure lines.

The third property of topology graphs defines the relations between intersection lines and roof outlines. In this research, the roof outlines are replaced by ground plans of buildings. Although the boundary of the roof is not explicitly visualized in topology graph, it is still important information that cannot be ignored. For each intersection line in the topology graphs, it will be either connected to an internal corner or intersected with map outlines; thus intersection lines are divided into three types to determine which of them should be intersected with map data. Besides, the defined types can give hints about the number of intersection points of each intersection line.

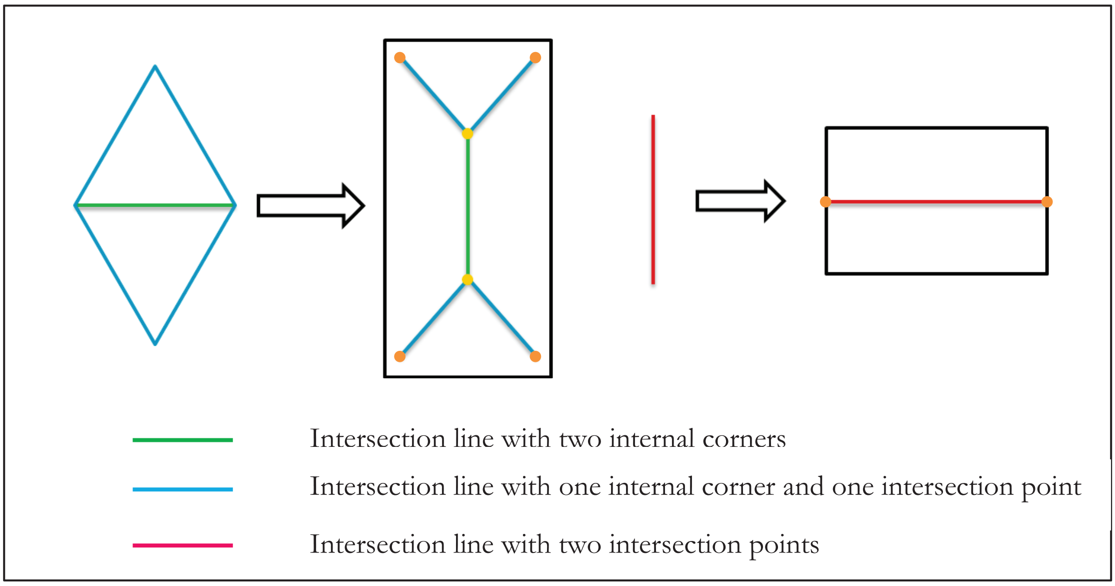


Figure 3-4 Three types of intersection lines

The three types of intersection lines are illustrated in Figure 3-4. The intersection line (dark green) which belongs to double circles in the topology graph is connected to internal corners of these two circles in structure lines figure. For the intersection line (blue) which only belongs to one circle in the topology graph, the situation could be that one endpoint of it is an internal corner while another is an intersection point with roof outlines. Both endpoints of the line segment (red) are the intersection points with roof boundary if the intersection line belongs to no circle. By classifying the intersection lines into three types, the endpoints of those structure lines are also divided into two categories. One is representing the internal corners (yellow dot) while the other one have the intersection points with roof outlines (orange).

The last property describes the relation between topology graph and the structure of whole building. It is usually the case that the step edge is located at where two different roof structures meet. Thus, each building can be divided into several partitions at the locations of step edges and the processes of roof detection and reconstruction will be done per partition. At last, they will be merged back to a whole building.

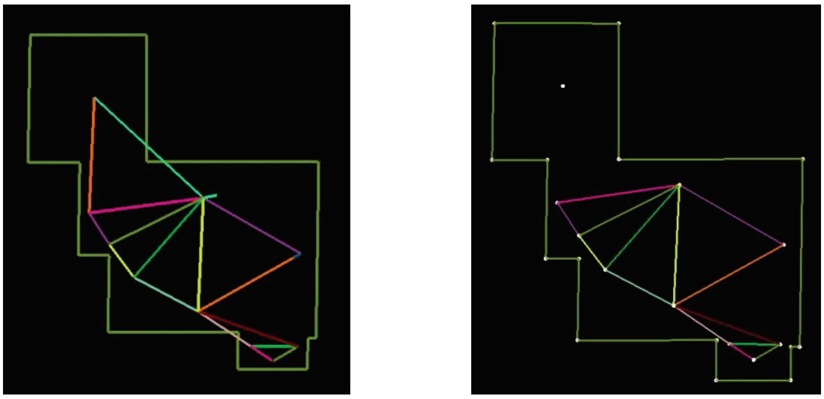
According to the properties of topology graphs, the algorithm of proposed method was developed and it can be divided into following three sections.

3.4. Partitioning

This section mainly introduces the preparation works which have to be done before the process of roof detection and optimization. Based on the last property of roof topology graph, different roof structures are divided by step edges. Moreover, the locations of step edges, most of the times, are related to concave corners of the building outlines and their extended lines. In this research, roof outlines are estimated from ground plans of the buildings; therefore partitioning works of map data with corresponding topology graphs and laser points are performed sequentially at the beginning.

3.4.1. Topology graph partitioning

The process starts with roof topology graph partitioning. By checking if there is any step edge within the topology graph, buildings with step edges are selected and labelled. Later on, the corresponding topology graphs are divided by temporarily removing step edges. In Figure 3-5, an example is given to show the result of topology graph partitioning. As a result, the original topology graphs are partitioned into two sub-graphs with the large one represents a complex roof shape and the single node refers to a flat roof.

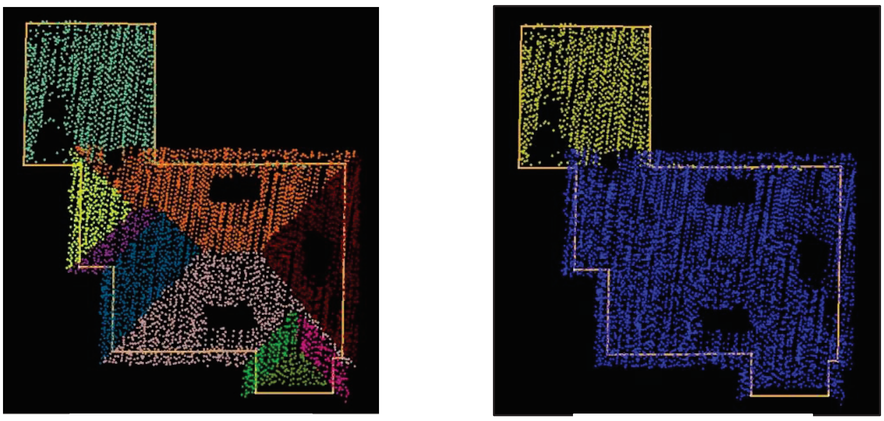


Before partitioning After partitioning

Figure 3-5 Roof topology graph partitioning

3.4.2. Laser points re-labelling

Next step is to re-classify laser points of the buildings based on corresponding sub-graphs. As each node in the topology graph refers to one roof segment, related laser points segments are obtained. For all roof segments which belong to the same sub-graph are assigned the same label. Thus, the numbers of labels are determined by the numbers of sub-graphs. The usage of re-classified laser points is to help to partition map data in the following step. An example is dipicted in Figure 3-6 as the laser points are re-classified and re-labelled based on related sub-graphs.

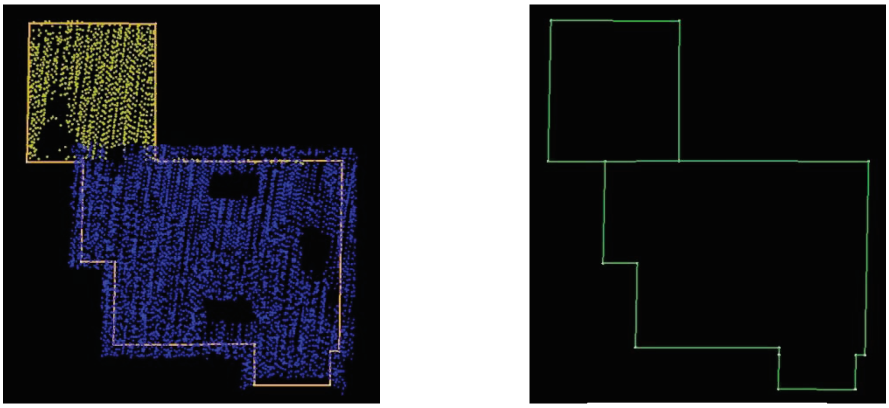


Before re-labelling After re-labelling

Figure 3-6 Laser points re-labelling

3.4.3. Map partitioning

The final step of partitioning section is to divide the ground plans by utilizing re-labelled laser points. The process is a 'split and merge' function. For each map outline which needs to be partitioned, the algorithm will decompose the original polygon into small ones at first. Then for each new divided polygon, find related laser points by testing if the laser data of the building are within a certain decomposed polygon. Next, count the numbers of laser points with different labels, assign the same label from the laser points which have the maximum amount. When comes to merge function, two adjacent polygons will be merged into one if they have the same label. If two adjacent polygons have different labels, keep both of them. Finally, as shown in Figure 3-7, each original map data will be partitioned into several new polygons based on re-labelled laser points. The detailed implementation and results are discussed and analysed in next chapter.



Before partitioning
Map with re-labelled laser points

After partitioning

Figure 3-7 Map partitioning by re-labelled laser points

3.5. Roof shape detection and optimazation

3.5.1. Initial roof skeleton

In order to detect roof shape and create roof faces of each new obtained map polygon, structure lines between adjacent roof segments will be derived firstly. In the research, the method used for obtaining intersection lines is the same as (S. J. Oude Elberink, 2010) did. As for step edges, they are already estimated by partition lines in the above section.

After intersection lines calculation has been made for each small partitioned polygon, the next step is to combine them into an initial roof skeleton with the help of roof topology graph. As it is explained in section 3.3, intersection lines will meet at one same point if they can form a circle in topology graph. Therefore, the algorithm will search for the circles in each corresponding sub-graph of partitioned map outline. Then internal corners can be derived by intersection lines of one circle. An example of expected result can be seen in Figure 3-8. However, those internal corners are just estimations and will be refined in later process.

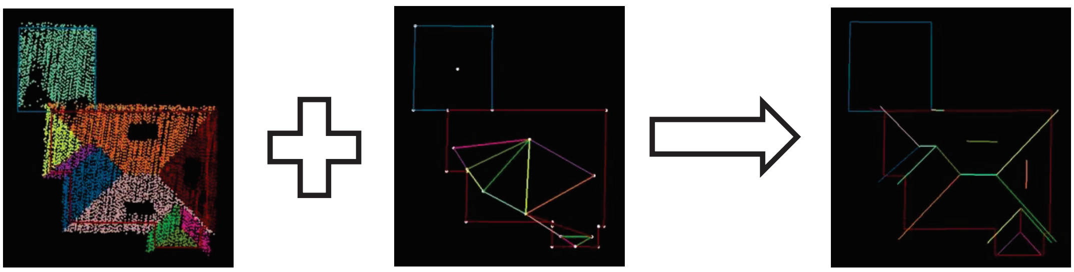


Figure 3-8 Initial roof skeleton creation from laser points and topology graph

3.5.2. Candidate corners

As now initial roof skeleton can be achieved by calculating the internal corners, the next step is to obtain those intersection points with building outlines. The initial locations of those points can be obtained by simply calculating the intersections between intersection lines and map data, but they are not always as logical as we expect. Based on common knowledge of roof shape and observation of the real world, some of the connection points should be exactly the corners of building outlines, and some should join the intersection points where extended concave corners meet building outlines. Another situation is in the gabled roof, where the connection point should be the middle point of the roof edge, in a common sense.

So we defined three types of possible intersection points and related sets of potential intersection points are calculated to be candidates from each partitioned polygon.

As seen in Figure 3-9, three types of candidate corners are depicted. The set of map corners are directly obtained from map data; middle points are derived by calculating the middle point of each building outline segment and extending corners are achieved by the intersection points of extended concave corners.

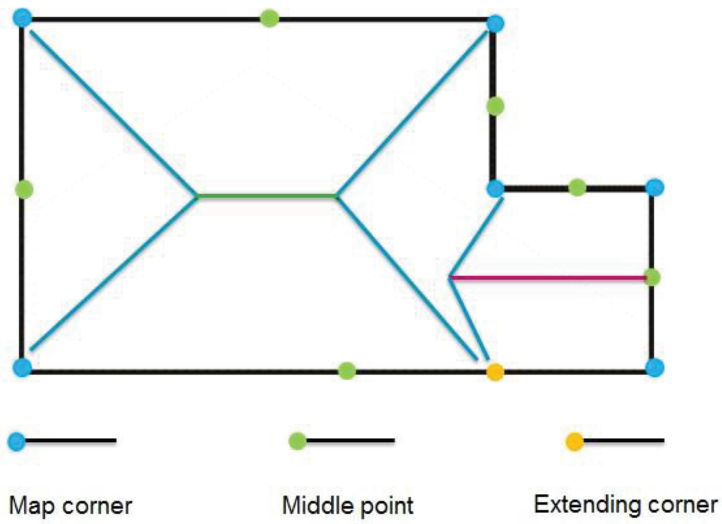


Figure 3-9 Three types of candidate corners with initial roof skeleton

3.5.3. Roof skeleton optimization

After calculation of candidate corners, combination between roof skeleton and building outlines can be processed and roof structures can be determined. During this processing, optimization will be made to the locations of both internal and intersection points by applied soft constraints.

Before dealing with intersection points, the locations of internal corners should be fixed. Constraint is defined for horizontal intersection lines of which both endpoints are internal corners. As is shown in Figure 3-10, building orientation is derived and compared with the direction of horizontal intersection line. Adjustment will be made for two endpoints by projecting them to the building orientation if the angle between two directions is within a threshold; otherwise the original location of the intersection line is kept.

Then the task is to make correct assignment between intersection lines and candidate corners. The determination is based on the distance between original intersection point and candidate corners. In order to make the correct choice, different selection criteria are created for the three types of candidates which based on different types of structure lines, common knowledge and statistics of experimental data. Possible weights may be given to the three point sets and weighted distances then can be calculated to determine whether the nearest candidate will be assigned to the intersection line or the original intersection point will be preserved if the distance is larger than a threshold. An expected result of hip roof optimization can be seen in Figure 3-11.

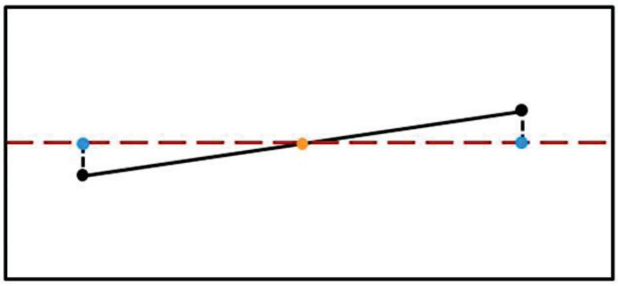


Figure 3-10 Original internal points (black) are adjusted to fit building orientation (dark red dash line).

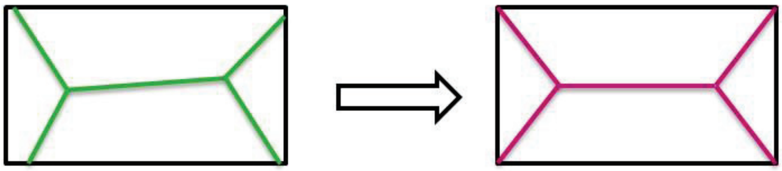


Figure 3-11 Expected result of roof skeleton optimization in a simple hip roof

3.6. Building modelling

3.6.1. Roof plane detection

Since roof skeleton is already optimized and integrated with building outlines, the structure of roof is determined. Next step of purposed method is to detect and reconstruct each roof face.

From the definition of topology graph, for each node in the topology graph, connected edges are namely intersection lines in reality. They are the interior edges of that roof face and the endpoints of those intersection lines will be part of the corners of that roof face. Moreover, the corresponding building outlines are divided by intersection points of structure lines. Then by combining the interior roof edges and related decomposed building outlines into a close polygon, a roof face is detected in 2D environment. An example is given below in Figure 3-12. Each roof face is determined with intersection line(s) and corresponding building outlines segments.

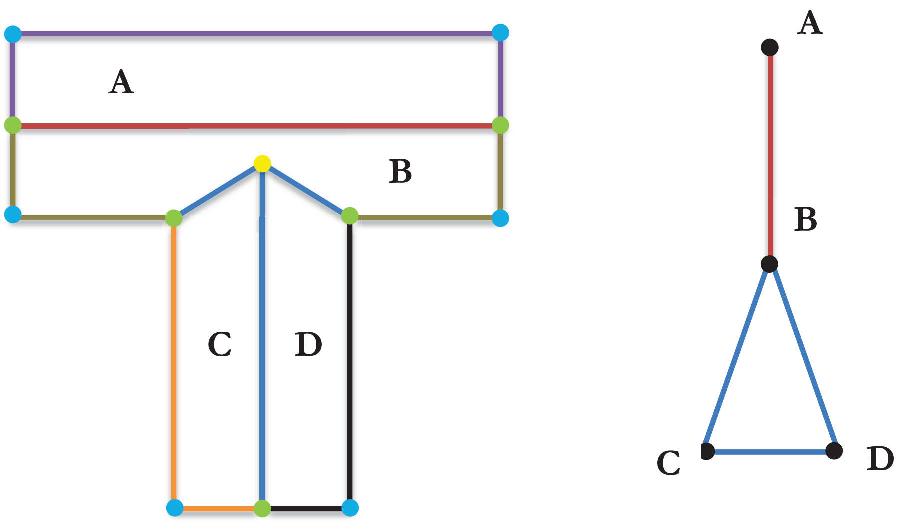


Figure 3-12 Roof faces detection from topology graph and building outlines

3.6.2. Height assignment

The process of height assignment is to convert 2D roof faces into 3D environment by giving consistent heights to the points of each roof face. In order to assign heights of 2D points from the same roof face, each roof face will be represented by 3D plane which fitter by corresponding laser segment at first. Then the points of each roof face can get their third coordinate through mapping them to the right plane. Finally, the complete roof surface of the building can be formed by all related roof faces.

A special case of flat roof is implemented in a different way. An average height of corresponding laser points is calculated instead of fitting a plane and all the roof corners are assigned to that same height.

3.6.3. Wall reconstruction

The reconstruction of walls in the research is quite simple. Because map data in the method is used for estimating roof outlines, it is always consistent between roof shape and ground building contour. As map data indicate the locations of walls, the reconstruction work can be done simply by connecting map corners with roof corners in the same X, Y coordinates. The derived polygons are vertical and precise to represent walls (see Figure3-13).

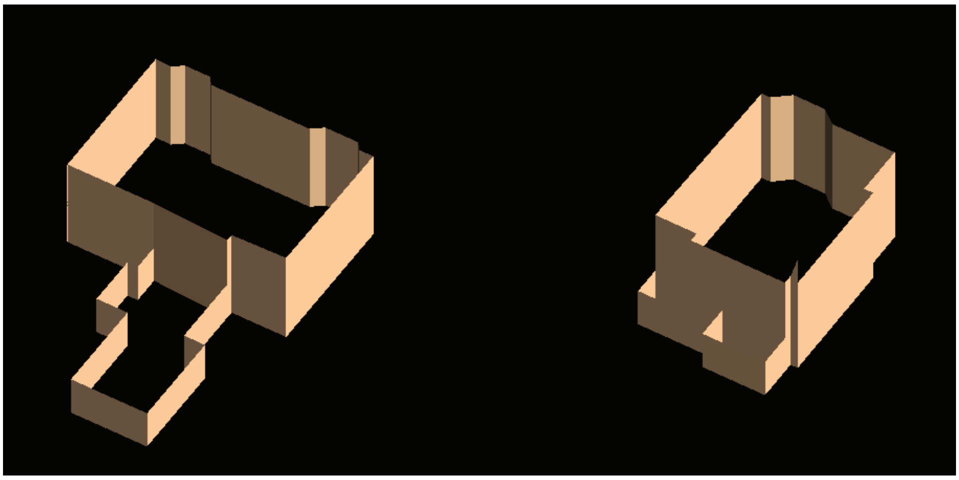


Figure 3-13 Reconstructed walls

3.7. Evaluation strategy

The evaluation strategy is composed of three sections.

3.7.1. Visual check

Not only for final models but for every step of proposed algorithm, intermediate results are outputted and visualized in Point cloud mapper (PCM). Through visual check and comparing with expected results or images, the evaluation of each step is conducted.

3.7.2. Roof shape optimization cost

This strategy is developed in this research for evaluating the results of optimized 2D roof structures. Two criteria are utilized in this paper for cost calculation. One is the displacements between original roof points and refined locations while the other one is the correctness ratio between each roof face with its corresponding laser points. In each building, all the costs will be finally summed up and normalized for visualization and analysis.

3.7.3. 3D modelling error

In the research, since a data-driven approach is proposed and each roof face is generated from laser points, it is not necessary for checking the residuals between roof planes and laser data. Instead of calculating the discrepancies between roof plane and related laser points in Z direction, the residuals of heights of roof shape corners are computed and visualized in PCM for 3D models evaluation.

3.8. Summary

In this chapter, a framework of methodology and workflow was presented at the beginning. Later, the properties of roof topology graph were analysed. Relations between roof segments, relations between intersection lines and relations between intersection lines and building outlines were revealed from topology graphs. Besides, the roof structure of entire building can also be indicated from topology graphs. Based on those properties, the method for roof shape detection was developed and a three-step algorithm for building reconstruction was described. During the reconstruction approach, candidate corners were defined and classified for roof skeleton optimization, and flexible constraints for intersection lines and points refinement were introduced. At last, the strategy of evaluation of proposed algorithm was presented in three aspects.

4. IMPLEMENTATION AND RESULTS

4.1. Experimental data

In this paper, the laser data used for experiment was the same as one of test data in (S. J. Oude Elberink, 2010). The test area is part of Enschede, the Netherlands. Acquisition was made by the FLV-MAP system and the point density is on average about 20 points per square meter. Both simple and complex roof shapes of the buildings are contained in this area. The map data was taken from the cadastral map of Enschede, with a map scale of 1:1000. In order to reduce the calculation time of the programme, 22 buildings were selected from the given data. The bird's view image of study area and input laser data with map polygons are depicted in Figure 4-1.

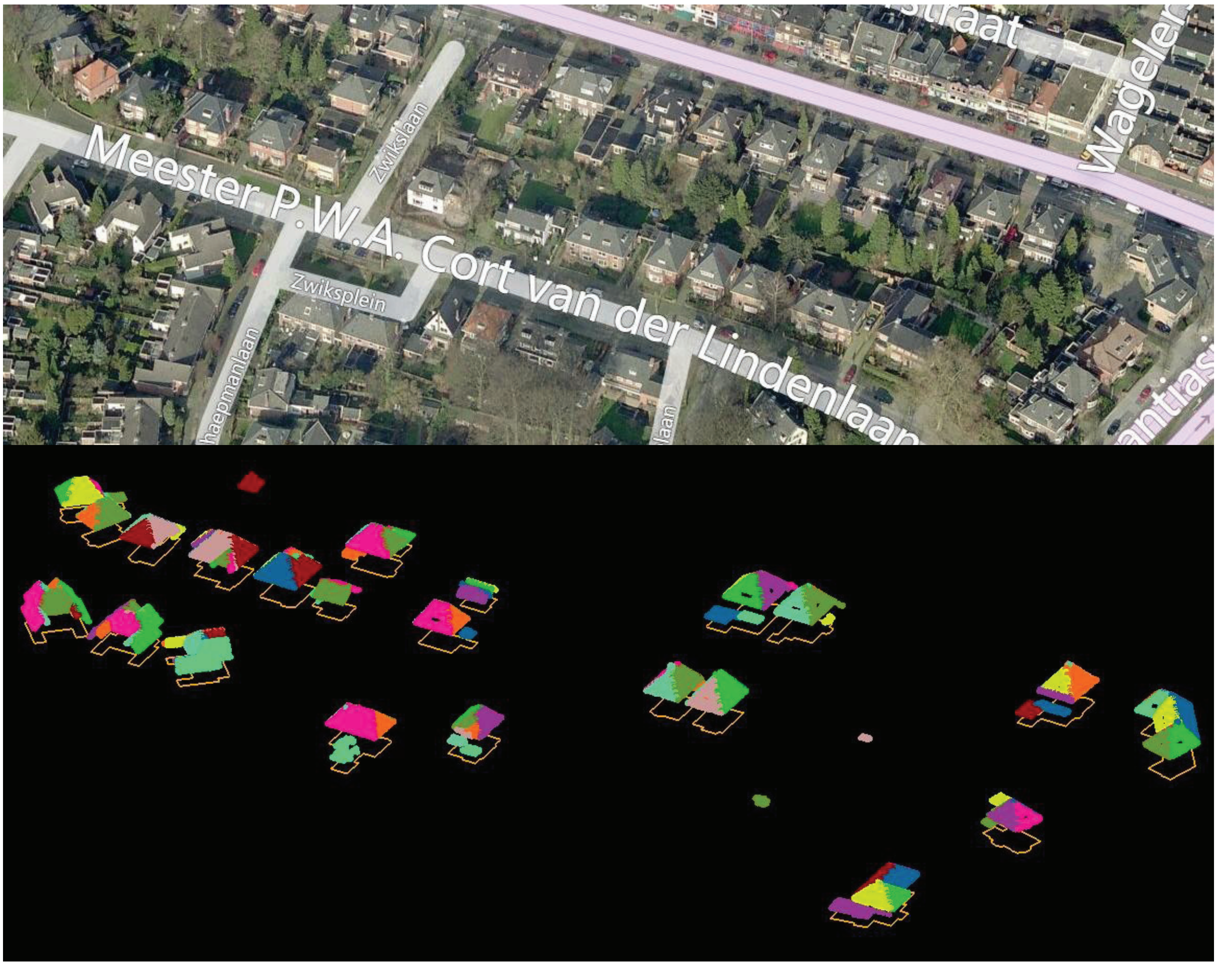


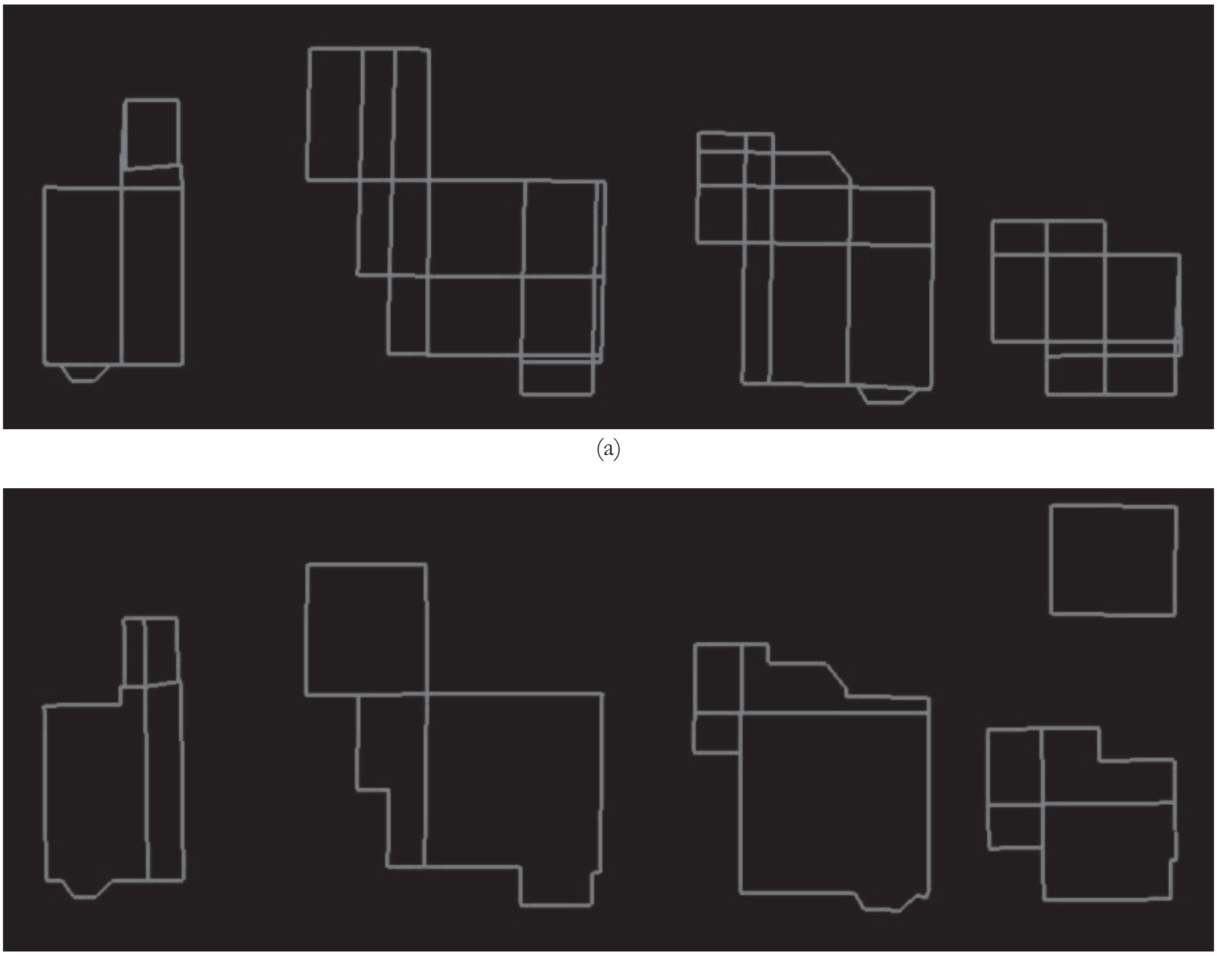
Figure 4-1 Bird's view image of test area (top) [Bing.com]
with input laser data and map data (bottom)

4.2. Partitioning

4.2.1. Implementation

As described in last chapter, partitioning process is made up of three sections. The first two steps were easily done by erasing step edges of original topology graphs and re-labelling corresponding laser points. The attribute of original building numbers were added to each sub topology graph after partitioning.

The main step of partitioning process was map decomposition which the results may influence the final models. Two splitting algorithms were implemented to the map data. The one was widely used for map partitioning. Each map polygon was decomposed by the extending lines from concave corners (Figure 4-2(a)). In order to reduce the number of partitioned polygons, if the edge of concave corner was not perpendicular with its both adjacent lines, it would not be used as partitioning line. Since the number of partitions could be more than 60 with many small and thin pieces for one complex building outline, it was time consuming for the programme. Thus second method for splitting polygons was developed.
In the second method, each pair of roof segments was selected firstly if they were connected by a step edge in the topology graph. Then a partitioning point was derived based on the centre of a TIN structure which was created from neighbouring point clusters of the pair of roof segments. Later, the location of partition point was refined by a snap operation. Each map outline segment was transferred to an infinite line to calculate point-to-line distance; if the distance was within a threshold, the partitioning point would be snapped to that line. For each partitioning point, this refinement was done twice as a proper location could be an intersection point of two lines. Finally, the map polygon was decomposed by building orientation and its perpendicular line through the partitioning point (Figure 4-2(b)).



(a)

(b)

Figure 4-2 the intermediate results of two partition methods.

In this paper, the second method was chosen as it was more fast and effective for map partitioning. After decomposing map polygon, each polygon was assigned the same label as corresponding laser points. Finally, these partitions were merged together based on their new signed labels.
The results of partitioning process are presented in the next section.

4.2.2. Results

Here are part of the results of partitioned map data with their related partitioned topology graphs and re-labelled laser points.

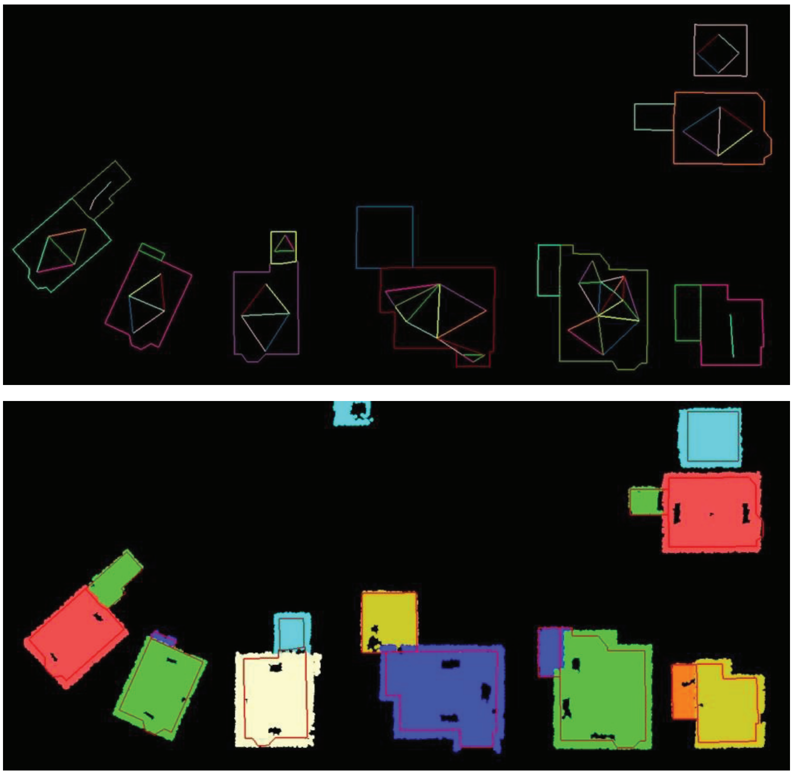


Figure 4-3 Partitioned map data with related partitioned topology graph (top) and Partitioned map data with re-labelled laser segments (bottom)

In Figure 4-3, each original topology graph was partitioned if it had any step edge with corresponding map data decomposed. Then as can be seen in the top figure, each sub-graph was related to each partition of map polygon. Laser points in the bottom figure were visualized by their labels. It is clear that each labelled segment was corresponded to a sub-graph in the top picture. Besides, the partitioned map data were almost suitable for corresponding laser points. The location of dividing line of two adjacent roof segments can be indicated by the common edge of related partitioned map polygons.

4.3. Roof shape dectection and optimization

4.3.1. Implementation

As this research has the same test area as (S. J. Oude Elberink, 2010), initial roof skeletons had already been created and can be used directly for further implementation. After having initial roof skeletons, the next step was calculation of candidate corners, as described in Chapter 3.

Three 2D points datasets were created from each partitioned map data. The map corners were obtained by transferring 3D map points to 2D coordinates. Dataset of middle points were calculated from each map line segment, but not all the line segments were used for calculation. If the length of line segment was less than 1 meter, the middle point can hardly be an intersection point. So only if the length of line segment was larger than 1m, it would be used for calculation. As for extending corners, they were derived by extending concave corners of the partitioned map outline. If the edge of concave corner was not perpendicular to its two neighbours (Figure 4-4(a)), it would not be used for deriving extending corners. Another selection was applied to calculated extending corners. If an extending corner was too close to an endpoint of the intersected line segment (Figure 4-4(b)), it would not be preserved.

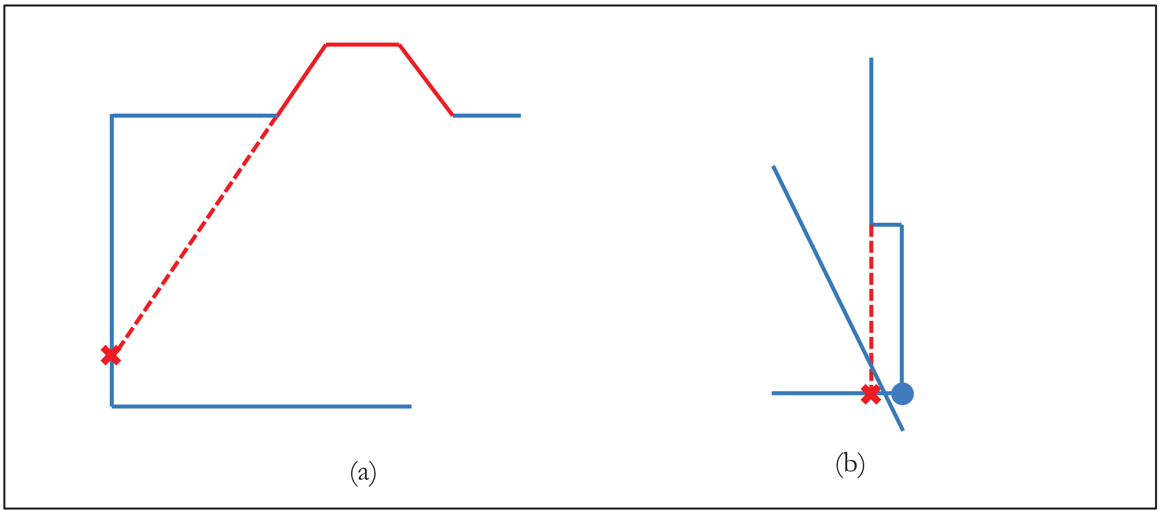


Figure 4-4 Two situations that were not used for deriving extending corners
The red crosses are false candidates which may lead to wrong intersection assignment.

Before assign intersection lines to candidate corners, internal horizontal intersection lines were refined and a rough statistic was made to test data. Intersection lines were classified into tilted and horizontal, and for each class, possible connections between intersection lines and candidates were observed through laser data and map polygon. The counting results showed that near 95% of tilted intersection lines were very likely to be connected with map corners, as the rest tilted ones may be connected to extending corners, two exceptions were found to be connected with middle points. When comes to horizontal intersection lines, the situations become complex. Only about 60% of them were likely to be linked to middle points. Half of the rest may be connected to extending corners, and another half may better keep the original intersection points. Three examples were given in Figure 4-5. The red dash lines indicated the correct locations of intersection points while the black dash lines showed the wrong assignment to the nearest candidate points.

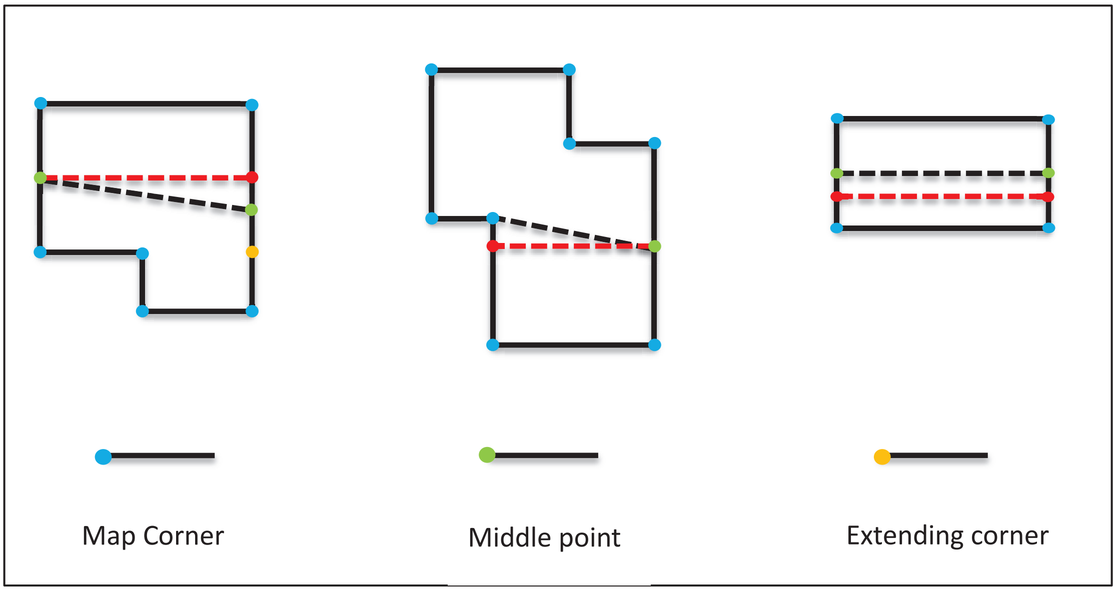


Figure 4-5 False intersection lines assignment

Based on the above study of test area, an optimal solution for intersection lines assignment was proposed. Two classes of intersection lines were defined and solution varied for each class. For each intersection point, three distances were calculated for making the selection of candidates. The three distances were depicted in Figure 4-6. Through trials and tests, different weights were applied to three distances and different thresholds for whether preserve original intersection position were made for two intersection lines classes. The optimization function for intersection points can be seen in Figure 4-7.

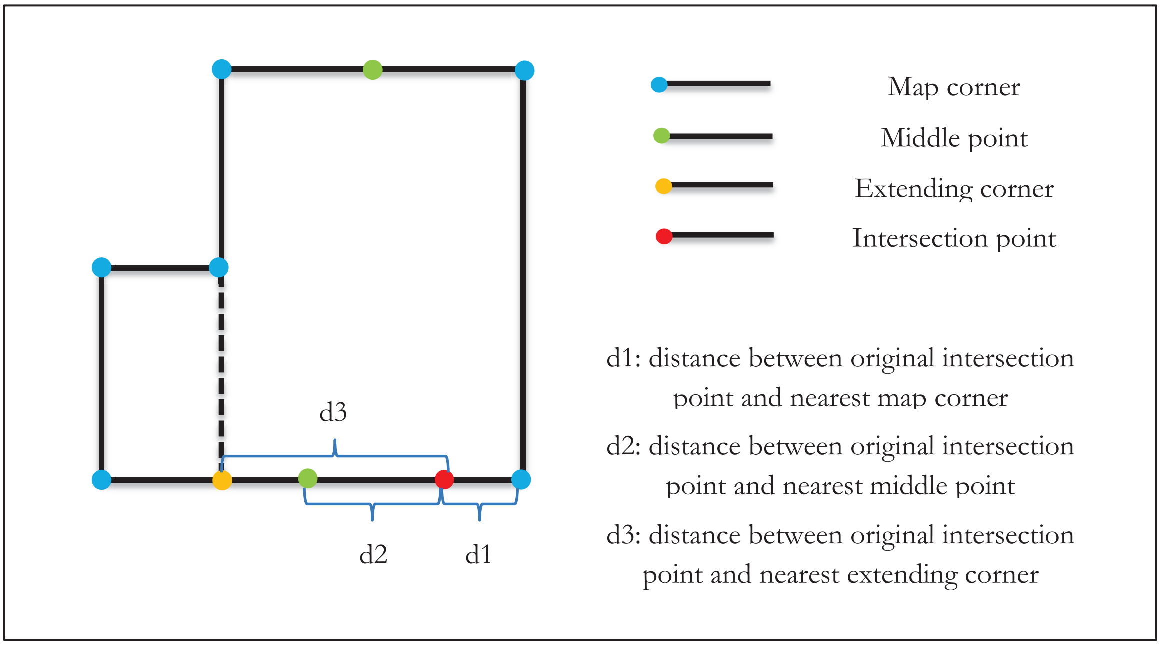


Figure 4-6 Three distances of one intersection point

For tilted intersection line:
If (d1<3*d3&&d1<6*d2&&d1<0.7) the line will intersect with nearest map corner.
If (6*d2<d1&&6*d2<3*d3&&6*d2<0.3) the line will intersect with nearest middle point.
If (3*d3<6*d2&&3*d3<d1&&3*d3<0.5) the line will intersect with nearest extending corner.

For horizontal intersection line:
If (d1<3*d3&&d1<6*d2&&d1<0.3) the line will intersect with nearest map corner.
If (6*d2<d1&&6*d2<3*d3&&6*d2<0.3) the line will intersect with nearest middle point.
If (3*d3<6*d2&&3*d3<d1&&3*d3<0.3) the line will intersect with nearest extending corner.

If none of above criteria is fulfilled, the line will preserve the original intersection point.

Figure 4-7 Rules for intersection points optimization

4.3.2. Results

Here are the results of roof skeletons optimization (see Figure 4-8). From the results, most of the intersection refinements were made as we expected, but problem still existed in few tilted intersection lines. The evaluation of optimization results and improvement will be displayed in next chapter.

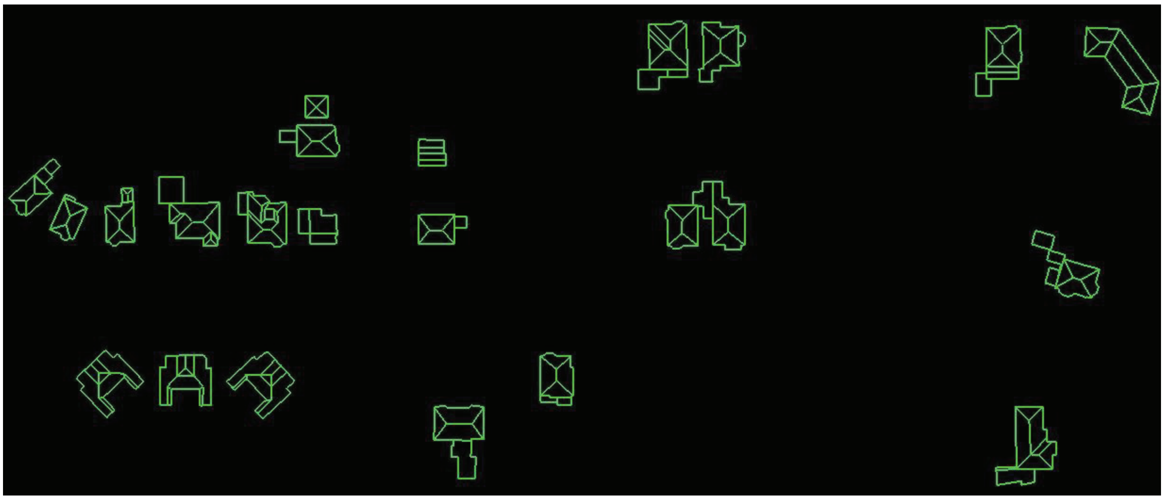


Figure 4-8 Results of roof skeletons optimization

4.4. Building modelling

4.4.1. Implementation

For roof plane detection, the internal edges of each roof face were derived with the help of topology graph, and each partitioned map outline was divided into two polygons by the internal edges. As the location of the node in each topology graph was obtained from the related roof segment, 2D roof face then can be determined by checking if the node was within one of those two polygons.
After roof planes were searched, the heights of roof corners were assigned as already described in Chapter 3. The roof faces of one building were calculated sequentially and later walls of the building were reconstructed by extruding points of each ground plan to assigned heights.

4.4.2. Results

The final results of proposed method are depicted in Figure 4-9. All of the 22 buildings were reconstructed. Roof faces were triangulated in PCM and boundaries of buildings were shown. The combinations of partitioned buildings back original were quite well since the walls were reconstructed from the partitioned map polygons which shared common edges.

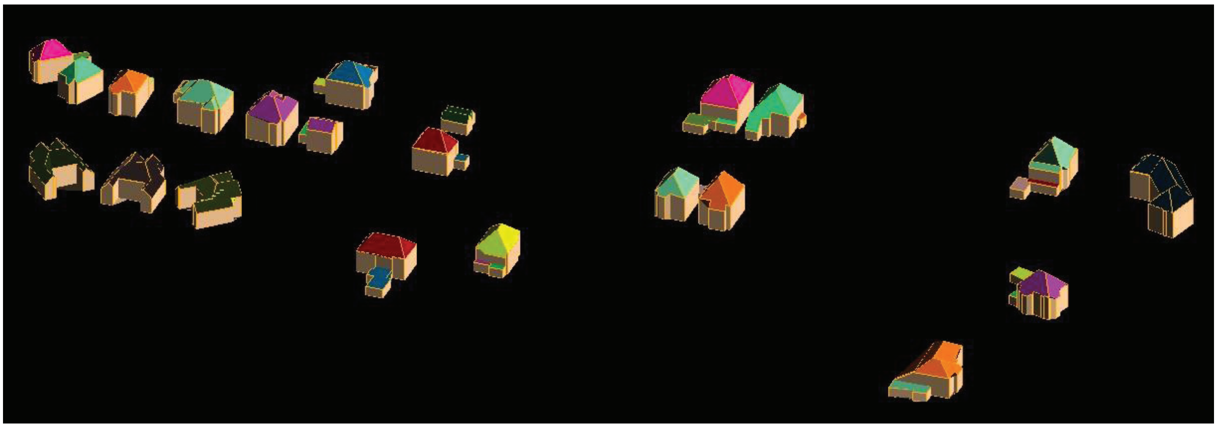


Figure 4-9 Final results of building reconstruction

4.5. Summery

In this chapter, the proposed method for building reconstruction was implemented with test data. Roof shapes were detected by creating roof skeletons from roof topology graphs. Then initial roof skeletons were optimized by common knowledge and study of buildings in test area. The presented optimization method was quite simple but efficient enough for test data. The results of roof shape detection and optimization proved that the algorithm was able to get preferable output. Finally, building reconstructions were made by combining roof faces into one and walls were reconstructed from map data. The results of building models were illustrated in Figure 4-9 and quantitative evaluation of output models and discussion of proposed method will be described in next chapter.

5. EVALUATION AND DISCUSSION

5.1. Evaluations of the results

The evaluation of final results is divided into three parts. At first, Visual check will give general comments on obtained building models. Later, two quantitative methods are used for evaluation of roof shapes and building models.

5.1.1. Visual check

The final models are already depicted in Figure 4.9. All the selected buildings were reconstructed through proposed algorithm. Either complex roof shapes or simple roof shapes were reconstructed by combined all the roof faces. And for combination of two partitioned buildings, there were no gaps between partitions because the wall was reconstructed by extruding the common edge of two partitioned map polygons.

However, there were some drawbacks of the final results. In Figure 5-1, several weaknesses are illustrated.

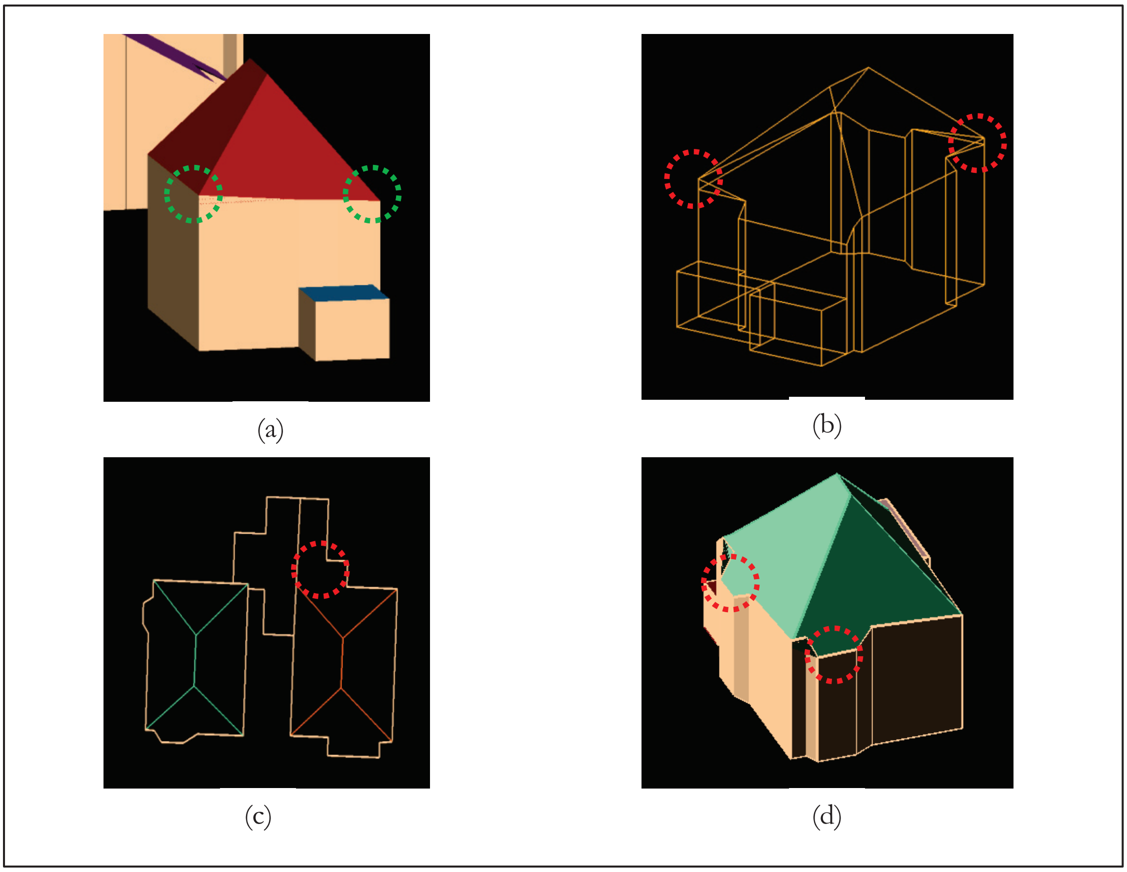


Figure 5-1 Weakness in final models

(a) Eave lines of some buildings are not horizontal as two endpoints are not in same height. Two reasons are responsible for this error. One is that the eave line is not perpendicular with normal direction of fitted plane, thus two endpoints will have different height. The other reason is that the roof points may have multiple heights which lead to the inconsistency problem.

(b) In boundary representation models, the problem of multiple heights of roof corners is obviously found. This is caused by the calculation of heights assignment. Roof corners which get repeated calculation may not have the same height since adjacent roof planes are not consistent. As a result, the heights of roof corners may have error.
(c) False face may be created if map partitioning does not work well. Then the lower part of the building will be regarded as part of the roof face. At last, long tilted roof face can be found in final results.
(d) Building extensions are treated as part of roof faces. This is caused by roof overhangs. As building extensions are occluded by roof overhangs, there is no laser point on them. They are classified as roof segments and will be regarded as roof outlines in modelling step.

5.1.2. Roof skeleton evaluation

In order to evaluate the results of optimized roof skeleton, a cost function is developed. The function is composed of two sections. One is the displacements between original roof points and refined locations while the other one is the correctness of each roof face with its corresponding laser points. Penalty cost may be added to tilted intersection point if it keeps its original intersection point. Detailed functions are described in Figure 5-2.
Then for each optimized roof skeleton, costs for all roof corners and roof faces were calculated and normalized cost was derived. Finally, cost of each refined roof skeleton was transferred to be residuals of related laser points.

d1: Adjust distance of internal points
d2: Adjust distance of intersection points
d3: distance between original intersection point and nearest corner point

Cost1: cost of an internal point

$$\text{Cost1}=\begin{cases} d1*d1 & d1\leq 1 \\ d1*10 & d1>1 \end{cases}$$

Cost2: cost of an intersection point

$$\text{Cost2}=\begin{cases} d2*d2 & \\ d3 & \text{if it is the tilted intersection point and not adjusted} \end{cases}$$

Cost3: correctness of one roof face

$$\text{Cost3}=\frac{\textit{the number of corresponding laser points which are within the roof face}}{\textit{total number of laser points which are within the roof face}}$$

Normalized cost of one building roof:

$$\text{Normal Cost}=\frac{\textit{total costs of one building roof skeleton}}{\textit{total number of calculated costs}}$$

Figure 5-2 Cost functions used for evaluation

Since the normalized cost of each building was quite small, in order to visualized and classified in PCM, they were all multiplied by 1000. Thus the results can be displayed and analyzed. In Figure 5-3, most of optimized roof structures got low costs of less than 10. Larger costs mainly caused by incorrectness of corresponding laser points. Another reason is that map partition results were not good enough for derived proper candidate corners and bad partition results will also lead to low correctness of related laser points.

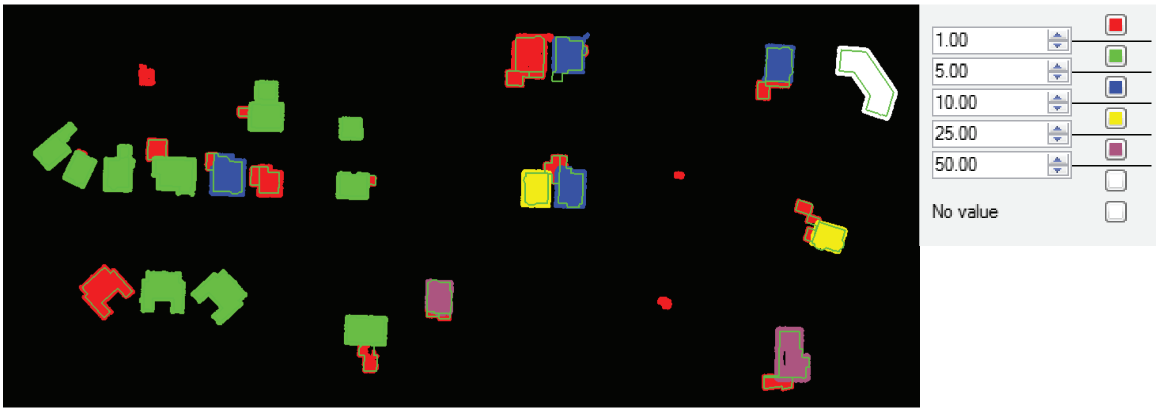


Figure 5-4 the results of normalized roof skeleton cost

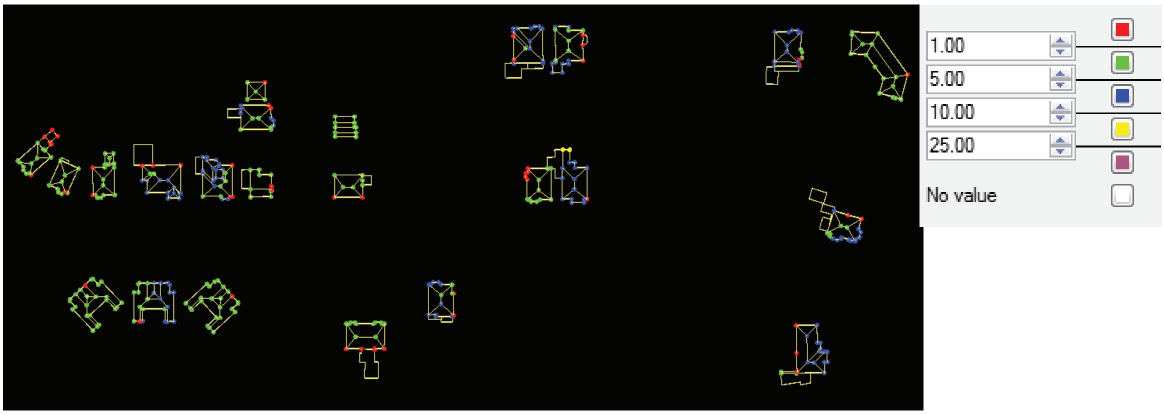


Figure 5-3 the results of roof corner residuals

5.1.3. Building models evaluation

As already mentioned that roof corners may have multiple heights, the residual between different heights can be used to describe the quality of final models. Unlike (S. Oude Elberink et al., 2011) proposed to classify roof corner points into three categories, here only general view of all roof point residuals are depicted and analysed. Each residual was calculated by largest height and smallest height of one roof point and the results of calculated residuals were visualized in PCM.

In Figure 5-4, although corner points may have different heights, but the variances of those heights were relatively small. More than half of the corner points in test data had a residual less than 5 centimetres while only two corners had a residual of larger than 10 centimetres. The reason for this problem was that the two points which should belong to lower flat roof face were mistaken to be two roof points of hip roof. The overall result of roof corner residual was acceptable and 3D models of buildings were considered to be good enough.

5.2. Discussiong and improvement of proposed algorithm

5.2.1. Partitioning

Here two map partitioning method are discussed. For the first method which used concave corners to decompose map data, as the map data was set to be a hard constraint for roof detection in the research, no generalization or adjustment actions were applied to decomposed polygons. Thus, for complex building outlines, the number of partitioned polygons could be more than 60. Besides, many small thin polygons were found if the two edges of building were almost collinear. They may cause problem for merge operation and influence the location of step edges. Moreover, no laser data were found within some polygons which will lead to map data missing. The last problem was that some building ground plan may not contain concave corners although there were step edges in related topology graph.

Possible improvements for this method are following: firstly, detect and make collinear edges to be one when decompose map. This can reduce both the number and small pieces of partitioned polygons. Secondly, use laser data for step edge estimation if there is no concave corner.

For second method, the main problem comes from the location of partitioning point. If the initial location of derived partitioning point is not ideal, then the method cannot work properly. Besides, the adjustment of partitioning point in this research was quite simple and only works if initial partitioning point was near the real step edge. So far, no efficient improvement can be made since the test data contains too many roof overhangs, then the initial location of partitioning point can always be shifted.

5.2.2. Roof shape detection and optimization

The improvement of this step mainly comes from the idea of weak primitives(Brenner, 2005). The sequence of internal point refinement and intersection point refinement will influence the result of optimization. And especially for internal points, two operations are offered when they are adjusted (see Figure 5-5).

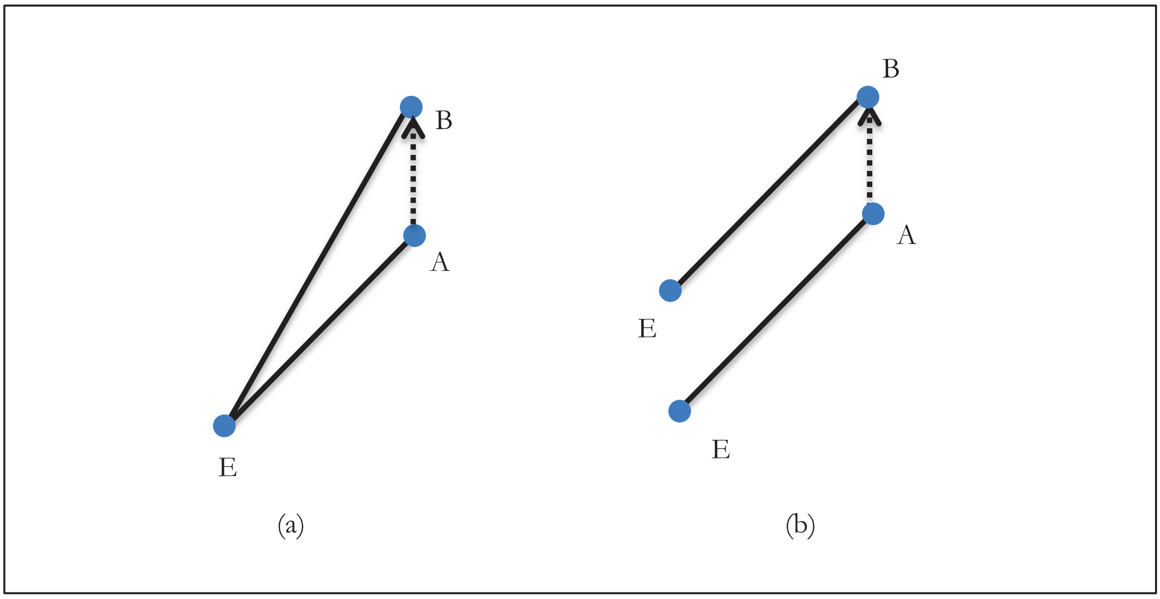


Figure 5-5 Two operations when adjust point A to B

When internal point A needs to be adjusted to location B, the other endpoint of have two choices. One is to keep the origin location (a) and the other one is the keep the original direction of that intersection line (b). The two operations may at last have different results of roof skeleton optimization.

Then it can be regarded as a global optimization problem for the roof skeleton. In order to have a better roof structure, for each situation of intersection line assignment, the defined cost of roof skeleton is calculated. Based on the lowest cost, the roof structure can be determined.

5.2.3. Building reconstruction

Since roof corners in this research may have multiple heights, the detected 2D plane may not be able to transfer to a real 3D plane because the related roof face points cannot form a plane. Then the so-called "face" in this paper may be two adjacent triangles (Figure 5-6).

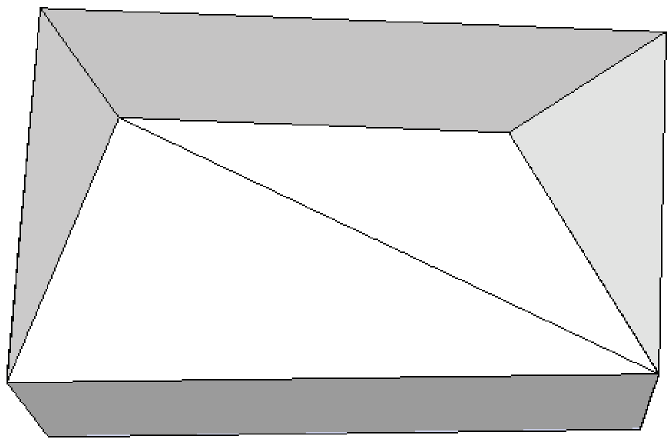


Figure 5-6 False plane which consist of two triangles

In order to solve the problem, a global optimization for roof face alignment is also needed. An example are given by (Zhou et al., 2012). Detected roof faces were controlled by a set of global regularities and constraints, and building models were finally generated from a series of coarse-to-fine iterations. In this research, roof faces are recommended to form an entire roof before the height assignment. Thus, for better and logical results of building modelling, a global optimization algorithm may be applied to detected roof faces alignment.

Besides, no roof overhangs was reconstructed in this research, this can be done by creating buffers for roof outlines. (S. J. Oude Elberink, 2010) had proposed to exceed the ground plan to reconstruct roof overhangs. A test will be made to laser segments for checking if the roof face has roof overhang structure.

5.3. Summery

In this chapter, the outputs of proposed method were evaluated from three aspects. The results of the evaluation showed that the final output models of this paper were relatively preferable and can be accepted. Later, for the problems which still exist in the process of test data, the reasons were discussed and some solutions and improvements were given.

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This research proposed a method for building reconstruction from ALS data and cadastral maps. From the implementation and results, some conclusions can be drawn:

- The map data in this research was used as a hard constraint which helps to create the walls and estimate the boundaries of roofs. Indeed, the walls were created well while most of the roof outlines should be larger the map polygons. The reason was that in test area, most building had roof overhangs.
- The properties of topology graphs were taken advantages of for detecting roof shapes in this paper. Relations among adjacent roof segments and intersection lines are explicitly indicated by corresponding topology graphs. The derived roof skeletons showed that topology graphs can well preserved the shapes of building roofs.
- A knowledge-based optimization was developed for intersection lines placement. Three types of candidate corners were defined for the assignment of intersection lines to map outlines. By determining the nearest weighted possible location for intersection points refinement and applying geometrical regularism to two endpoints of internal horizontal lines, each initial roof skeleton was adjusted to a preferable shape.
- Although final building models were evaluated to have good results, the reconstructed models still had problem in displaying true 3D roof face. The problem was important in solid reconstruction so that further improvement for roof shape refinement should be done.

6.2. Answers to research questions

1) How to deal with inconsistency between extracted features and ground plan?
   The inconsistency problem always happened where structure lines do not intersect with ground plan at a logical location. In this research, a knowledge-based optimization method for roof skeleton was proposed and candidate points were derived for a better intersection lines assignment.
2) What information can be indicated from roof topology graphs?
   Relations between roof segments, relations between intersection lines, relations between intersection lines and building outlines were revealed from topology graphs.
3) How to derive roof structures using the properties of topology graphs?
   With the information from topology graphs, the structure lines were firstly derived from laser segments, and then internal corners can be calculated from the circles in topology graphs.
4) How to define and formulate well-structured hard and soft constraints for roof features?
   In the research, the map data were used as hard constraints for roof structure optimization. As for soft constraints, the candidate points and weighted distances which used for intersection point determination was a kind of soft constraint.
5) Which optimization algorithm is going to be used in my situation?
   The optimization algorithm used in my situation was defined based on common knowledge and study of buildings in test area. The algorithm finally will make a choice for each intersection line to make them connect to a logical location with map data.
6) How to implement the optimization algorithm with experiment data?
   Before optimization, candidate points were calculated. When implemented optimization algorithm, the internal corners were firstly shifted to refined location where made horizontal internal line to be

consistent with building orientation, then for intersection line assignment, weighted distances were calculated for determine which candidate point should be assigned to the intersection line or preserve the original intersection point.

7) How to evaluate the performance of proposed workflow and algorithm using the experiment data? The evaluation was composed of three sections. Visual check for general looking of the results; proposed roof skeleton cost was defined for 2D roof shape evaluation. The lower cost calculated, the better roof shape obtained. The 3D models were evaluated from the residuals of roof corners as they may have multiple heights.

6.3. Recommendation

Although the proposed method works fine for test data, it is only a small dataset with other inputs were assumed to be correct. In order to make the algorithm more robust, several recommendations are given below:

- In the proposed algorithm, topology graphs were already given without obtaining them from laser data. Since the laser point may have problems such as missing data and false segments, how to obtain correct roof topology graphs are important for this method.
- During the process of map partitioning, the results of both implemented algorithm were not satisfied. Since map partitioning results could have a significant influence on the final results. An efficient way to decompose map data is urgent.
- The roof skeleton optimization algorithm in the research is relatively simple, the thresholds and weights for candidate points only had a small influence on final output since the location of initial roof skeleton was already quite well. However, threshold and weight may matter in other situations, so how to derive those thresholds and weights may become problem.
- As discussed in last chapter, the roof shape may have inconsistency problem in roof points' heights. Possible improvement can be made through global optimization method. To realize the method, constraints and regularities are needed, so how to define them may lead to a new search.

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