Outlining Buildings Using Airborne Laser Scanner Data

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By
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Abstract

Buildings represented by their 2D boundaries are used in many applications such as cadastre, town planning or transmitter placement in telecommunication. The reconstruction of 3D building models also requires the use of 2D Building outlines.

Traditional method for creating building outlines making use of photogrammetric workstations is time consuming, cost intensive and requires trained and skilled operators. Face to the high demand, speeding up the process by automatic procedures has become a necessity.

Airborne Laser scanner data with its increasing point density offers the opportunity to determine building outlines. Extracting 2D building outlines from lidar data has been a research topic for many years. These solutions, using various strategies, are implemented with low point density datasets and produce some results not accurate enough as explained by most of the researchers involved in this topic. The present study proposes another algorithm for automatic extraction of building outlines using exclusively high-density point clouds. In this research, a 2D outline stands for a roof's contour made of straight edges with regular angles in most of cases.

After segmentation of the point clouds into planes, points reflected by building roofs can be extracted. A modified version of the Convex Hull algorithm is used to collect the outer points. Applying the least squares adjustment technique, line segments are fitted within these outer points. The main orientation of the building is computed by intersecting the most sloped roof face with a horizontal plane or in case of flat roofs, by considering the azimuth of the longest edge. Three different strategies are considered while reconstructing buildings' outlines. Because at least 75% of buildings' outlines have only right angles, a first attempt of the boundary will be created using only right angles. In case of unsatisfactory results, a second option will be considered where the angles are multiple of 45^{o}. If it happens that the resulted boundary is still unacceptable, in a last approximation, the building angles will not be forced anymore to have predefined values. The obtained edges will be displaced towards the exterior of the roof such that the maximum of points fall inside the outline. Short segments are then removed. Two criteria are used to automatically appreciate the quality of the outline: The percentage of laser points that fall inside the outline and the difference in surface between the computed outline and the polygon made by outer points. In order to make this algorithm suitable for any airborne laser point clouds, the different thresholds are computed automatically on the flow based on the point spacing of the dataset. The latter is obtained from the triangulated irregular network of the points.

The newly acquired laser scanner data for the town of Enschede has been used to test the algorithm. 100 Buildings have been selected. Diversity in shape, size and orientation were the main selection criteria.

To evaluate the performance of this algorithm, in a first step, the computed outlines have been superposed with laser points, orthoimages, building footprints obtained from photogrammetric methods and reference data created manually. In a second step, a quantitative analysis has been conducted where six parameters have been defined to measure the quality of the computed outlines with respect to the reference ones: The percentage of laser points that fall inside the outline, the difference in number of corners, the difference of the main orientations, the extra difference area, the missing difference area and the average distance between outlines. The robustness of the algorithm has been evaluated by measuring the influence of the point density. A comparison with one previously designed method was also achieved. Finally, the limitations of the algorithm have been highlighted.

The outlines produced by the designed approach reflect the shape of the buildings with a high precision. However, the analysis of these results reveals some limitations that need to be fixed with further work.

Keywords: Airborne laser scanner data, roof outline, Building knowledge, Performance analysis.

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1. Introduction

1.1. Motivation and problem statement

Building representations are used in many applications such as cadastre, town planning, architecture, or transmitter placement in telecommunication. Other potential applications are analysis of propagation of noise and estimation of real estate taxes. Buildings are mostly represented by their 2D boundaries or by their 3D models. The reconstruction of 3D building models also requires the use of 2D outlines. The determination of 2D building outlines is therefore a fundamental task to solve many issues.

Building outlines delineation can be done through analytical or digital photogrammetry techniques. But these manual and interactive modes are time consuming and cost intensive. In addition, they require trained and skilled operators. Face to the increasing demand of 2D digital map and 3D building models, speeding up these processes by automatic procedures has become a necessity. Laser scanner data offers such a possibility.

Laser scanner provides dense and geo-referenced points describing all possible reflective terrain objects including bare ground and buildings. Laser data makes use of Global Positioning System (GPS) to determine the position of the sensor, Inertial Navigation System (INS) to determine the attitude of the sensor and laser beams to determine the range between the sensor and the target points. The increasing point density of airborne laser scanner data triggers research in the extraction of building outlines.

As prerequisites for building boundaries extraction from laser scanner data, the point clouds have to be classified into buildings and non-buildings classes. Thus buildings can be identified and points describing these buildings extracted.

2D Building boundaries reconstruction from laser scanner data has been a research topic for many years. Though several solutions have been proposed in literature, they present some deficiencies as shown by some researches below. Weidner and Förstner (1995) extract building extents from high-resolution digital elevation models using range image but they suggest further work to improve the results achieved. Haala and Brenner (1997) extract planar roof primitives from laser altimetry data but the boundaries of buildings are derived from ground plans. They assume that optimal results can be achieved only by the use of additional data. Morgan and Habib (2002) considered difficult to extract building outlines from aerial laser scanner data with a high degree of certainty and therefore recommend the use of aerial photos. Alharthy and Bethel (2002) suggest a method for extracting features from lidar data but the building edges are forced to have only two directions. Clode et al (2004) use the first pulse/last pulse return differences of an aerial laser scanner system to delineate buildings but further works are required to make the algorithm robust.

Most of the researchers claim that building outlines delineation is not a straightforward task. They conclude their papers by suggesting further work and by asserting that a higher point spacing of laser scanner data can lead to a better accuracy in the determination of building outlines. Thus, the accurate determination of building outlines from airborne laser scanner data remains an on-going research topic.

Taking into account that additional information sources such as ground plans and multispectral imagery are not always available, this research, motivated by the above observations is intended to derive automatically 2D building outlines from point clouds exclusively.

Section 2 of this chapter will identify the research objectives and the research questions. It will also highlight the intended innovations. Section 3 will focus on the approach to use in order to achieve the objectives. The last section will present the structure of this thesis.

1.2. Research identification

1.2.1. Research objective

The main objective of this research is to design, implement and analyze an algorithm for automatic extraction of 2D building outlines from point clouds. But prior to that, a review of existing methods will be made. The task is to derive a polygonal description of building outlines from the points that reflected from the roof of buildings. The method should be preferably automatic without any interaction. It should be successful for most types of buildings. The performance of this algorithm will be evaluated and compared to existing methods and to the ground truth.

The result of this algorithm is a set of points with their coordinates including the topology that describes how these points are related to each other in order to reconstruct the outlines.

Upon completion of this study, researchers involved in 3D building models reconstruction can easily achieve their goal with more automation and a better accuracy. Furthermore, it will be easier and faster in production lines, using point clouds data to derive accurate 2D building outlines for mapping purpose. Most often, building boundaries are created based on wall corners. Considering the target application, if the difference between wall corners and roof corners doesn’t matter, then laser scanner data can be used to produce rapidly accurate 2D maps.

1.2.2. Research questions

This research intends to develop a data driven approach for the determination of 2D building outlines. For this purpose, several questions have to be answered:

- What are the different methods proposed in literature to extract 2D building outlines using airborne laser scanner data?
- Based on the knowledge gained from the information contained in the laser data and the weaknesses of the previously developed methods, how can a new algorithm be designed for the extraction of 2D building outlines? How can the use of some constraints such as parallel and perpendicular edges improve the determination of outlines?

- What is the performance of this algorithm in terms of robustness and accuracy with respect to the ground truth and previously developed methods?

1.2.3. Innovation

The innovations intended are:

- the development of a fully automatic algorithm or at least an algorithm with a high degree of automation where the different thresholds are automatically computed and not typed by the user;
- a procedure suitable for most types of buildings and not only buildings with right angles;
- an accuracy better than the ones achieved so far;
- the use of a high point density data to test the algorithm;
- a meaningful quantitative accuracy assessment.

1.3. Method adopted

This research will be conducted in three different parts as shown by figure 1.1.

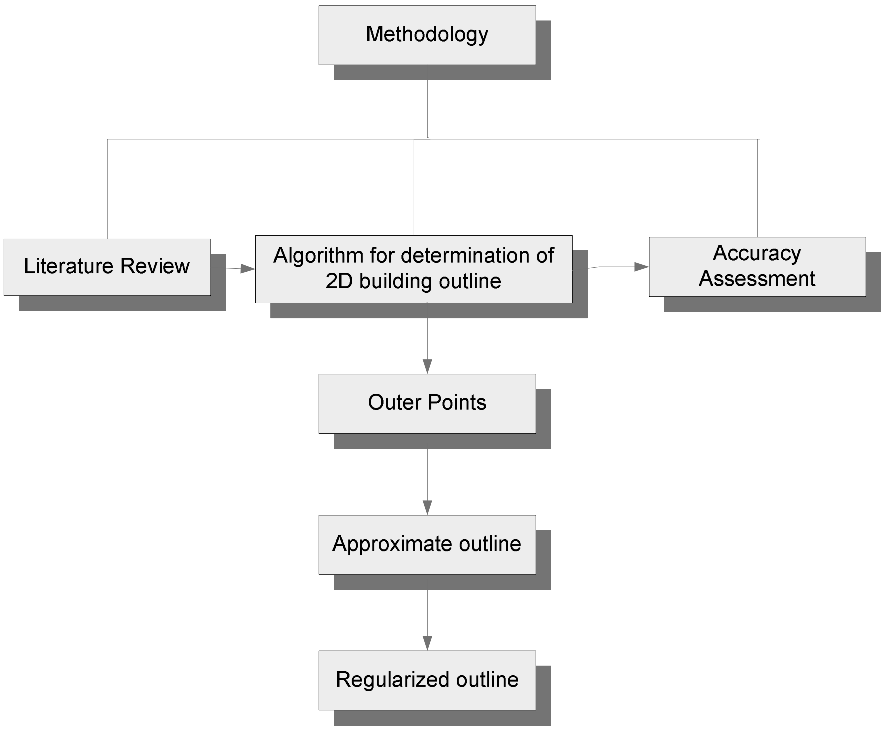


Figure 1-1: Methodology of thesis

In the first part, a literature review will be accomplished on extraction of 2D building outlines from point clouds. Existing semi-automatic and automatic methods will be described. After explaining the methodology of the author, a comment will be provided on the pertinence of this approach.

In the second part of this research, an algorithm for the determination of 2D outlines of buildings from point clouds will be designed and implemented.

The design of the new algorithm involves three steps:

- The detection of outer points;
- The determination of an approximate outline;
- The improvement of the outline: The determined polygon from the previous step will appear very ragged. Regularization and adjustment techniques need to be applied as most buildings have regular geometric shapes with straight edges and regular angle corners. Unnecessary points will be deleted and the others will be adjusted if needed. Different options could be considered. Among others, Minimum description length-based polygon simplification, Douglas-Peuker algorithm, vertex reduction principle, least square adjustment, maximum likelihood estimation and Bayesian Maximum a Posterior estimation. Within the process of finding the best outline, it will also be considered the possibility to automatically recognize some constraints in the building outline like parallel and perpendicular lines.

The third part of this research will concentrate on the analysis of the performance of this algorithm. This evaluation will take into account the number of edges, their position and their orientation. A visual check as well as a quantitative analysis will be achieved. The results obtained will be compared to the ground truth and to existing methods found in literature. Knowing that building edges extracted from aerial images represent building walls, the difference between roof outlines and building footprints will be considered in the analysis of the performance of the algorithm to be designed.

1.4. Structure of the thesis

Chapter 1 introduces this study and describes the objectives, the research questions as well as the method adopted. Chapter 2 reviews different techniques found in literature for the extraction of 2D building outlines. Chapter 3 proposes another approach for the determination of 2D building outlines. The implementation of this approach as well as the results obtained are described in chapter 4. An accuracy assessment on the designed methodology is presented in chapter 5. Chapter 6 provides the conclusion of this research and some recommendations.

2. Review of techniques for the determination of 2D building outlines

2.1. Introduction

The extraction of 2D building outlines is generally performed in three different steps:

1. The identification and extraction of buildings with the removal of extraneous objects;
2. The selection of points or pixels of interest useful for the determination of the boundary;
3. The refinement of the approximate outline using some adjustments techniques and constraints relative to building knowledge.

Existing approaches for reconstructing 2D building outlines can be classified into three different groups.

The first category uses exclusively range images to determine the boundaries. The original irregular points are resampled into a regular grid. The majority of researchers reflect on this technique as processing irregularly distributed points seems more difficult than considering regular grid points. Some of these methods will be described in section 2.2.

The second category uses solely the raw point clouds without any transformation into image. The aim is to avoid errors caused by interpolation during the resampling process. Section 2.3 focuses on some of these techniques.

In the third group, researchers rely on other sources of information such as ground plans, GIS data or multi-spectral imagery. The main reason for this is that lidar points are not selective. They are randomly distributed and therefore do not match necessarily building boundaries. Thus, the determination of outlines using lidar points is not straightforward. See some examples of these methods in section 2.4.

For each of the approaches described, first, the methodology will be highlighted. Next, attention will be focused on the evaluation of that methodology by its author. Finally, our appreciation on the quality of the results will be presented.

For most of the papers referenced in this chapter, the main objective is to reconstruct 3D building models. But the determination of 2D building outlines is an important step in this process.

In section 2.5, some existing polygon reduction techniques will be described. The next section will summarize the literature review and the last one, 2.7 will justify the need to develop a new methodology.

2.2. Techniques using range images exclusively

In the methods presented in this section, irregularly distributed laser scanning data are converted into regular grid in order to facilitate the data processing.

2.2.1. [Weidner and Förstner, 1995]

The approach of Weidner and Förstner, (1995) consists of three steps: automatic generation of a high resolution Digital Surface Model (DSM) using stereo matching techniques, detection of buildings and reconstruction of 2D building outlines for each detected building.

The software package MATCH-T is used to generate the DSM. This technique may use different sources of information including digital imagery. MATCH-T makes use of feature pyramids. For each pyramid layer, homologous features are detected and matched and their 3D coordinates are computed. Starting with the lowest resolution pyramids, the coordinates are refined successively with the higher resolution pyramids.

The detection of building in the DSM is based on the fact that buildings are higher than their surrounding surface. First, an approximate topographic surface is computed using a mathematical morphology operation called opening whose basic effect is to remove some of the foreground pixels. The structuring element size is chosen such as it is not entirely contained in the building outline. The difference between the original DSM and the approximate topographic surface contains information about buildings. A simple threshold, derived from prior generic knowledge is used to identify buildings.

The next step is to isolate individual buildings. In order to identify the different segments, connected components are computed and each segment is labeled. A bounding box is computed for each segment. Using the size of the segment and the position of its bounding box, a refined segmentation is performed, rejecting incorrect building segments such as trees. In addition, segments whose bounding box exceeds the margin of the dataset are rejected as it is likely that without the missing information, the building cannot be reconstructed.

To reconstruct geometrically the buildings, an object-related approach is applied. Two types of models are considered, parametric models for simple buildings describable with few parameters and with ground planes being rectangles and prismatic models for complex buildings or blocks of connected buildings.

For the parametric models, the bounding box of a segment is used as 2D outline.

The reconstruction of 2D outlines for prismatic models is performed in several steps. First, the interior pixels of the segments are removed. After vectorization, the outline points are determined and sorted in a clockwise order. Points on straight lines between two neighboring points are eliminated. A merging algorithm is then applied to eliminate discretization noise meaning points that create with neighboring points a triangle whose height is lower than a predefined threshold. This minimum height has been computed based on the resolution of the input data. The local minimum description length (MDL) approach is now used to reshape the outline polygon.

The purpose of statistical modeling is to discover regularities in observed data. The success in finding such regularities can be measured by the length with which the data can be described. This is the rationale behind the Minimum Description Length (MDL), principle introduced by Rissanen (1978). " The MDL Principle is a relatively recent method for inductive inference. The fundamental idea behind the MDL principle is that any regularity in a given set of data can be used to compress the data, i.e. to describe it using fewer symbols than needed to describe the data literally. " [Grünwald, 1998]

The theory of this second merging phase is to impose rectangle conditions at neighboring points. In the present case, the MDL-based polygon simplification method has been applied by locally analyzing four consecutive points. The idea is to change the position of the two middle points or to replace them by another one, possibly introducing a right angle with the constraint that the area of the polygon has to remain constant. It is an iterative process which is performed until the description length cannot be further reduced. A final adjustment is performed taking into account some constraints such as perpendicular or collinear edges. This estimation process fuses the boundary points obtained from the discretization-noise cleaned data and the inferred outline from the MDL step.

An example of the results obtained is provided in figure 2-1.

The algorithm of Weidner and Förstner (1995) has been applied to different datasets. For parametric buildings, a test data with a DSM resolution of 0.5m in x and in y-direction was considered. For complex buildings, a dataset with 5m resolution in each direction has been used. According to the authors, the results are quite remarkable. However they suggest for further work the following:
- The global application of MDL instead of a local application;
- The investigation of symmetric and semantic constraints about rows of buildings.

The use of image introduces some errors during the interpolation step. The designed method is a semi-automatic method as mathematic morphology and vectorization are not fully automatic. The first requires structuring elements whose dimensions depend on the size and shape of buildings available in the data while the second needs some extra operations to finalize the vectorization. No accuracy assessment has been done for this method.

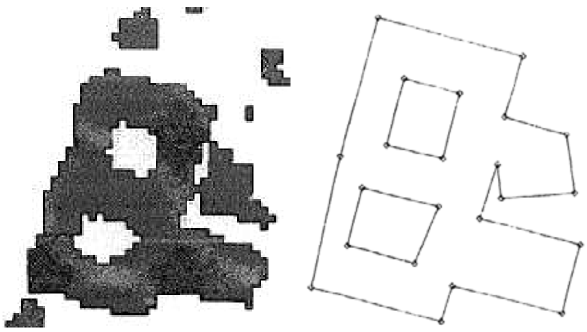


Figure 2-1: Example of 2D outline (Image + outline), [Weidner and Förstner, 1995]

2.2.2. [Morgan and Habib, 2002]

Before dealing with 2D building outlines, the research conducted by Morgan and Habib (2002) focuses on two items: the resampling of the laser data while converting raw point clouds into range images and the detection and extraction of buildings from lidar data. The determination of accurate 2D outline which occurs during the process of extraction of buildings requires appropriate preliminary steps, among which the resampling of the raw laser data.

In order to achieve good results during the interpolation while resampling laser data, Morgan and Habib (2002) suggest the extraction of breaklines as a prior step. During the resampling process, two factors have to be considered. The former deals with the resample location related to the pixel size. The latter is made of the resample values, thus the interpolation method. To avoid loss of information as well as keeping redundancy as minimum as possible, it is suggested the dimension of a pixel size of $1/\sqrt{n}$ with n being the number of points within a unit horizontal area. For the interpolation method, the authors suggest a least squares local first degree polynomial adjustment.

The proposed algorithm for building detection and extraction has the following steps: segmentation of laser points, classification of laser segments, generation of building hypothesis, verification of building hypothesis and extraction of building parameters.

Segmentation of laser data is the process at the end of which laser points that have common characteristics are grouped. In this case, segmentation means extraction of points that fit into a plane. As prerequisites for the segmentation process, adjacency criteria and grouping criteria have to be defined. To generate the adjacency information, a two or three dimensional triangulated irregular network (TIN) of the laser points is computed. As Hough Transform, one of the methods used for grouping by switching from data space to parameter space does not consider adjacency between points; region growing with the use of similarity of the orientation of the surface normal vectors as grouping criteria has been preferred. In order to avoid blunders, care has to be taken while considering threshold values for the deviation from the growing plane.

The next step is the classification of laser segments into building and non-building classes. This is done with a morphological filter. The idea is to classify the laser points based on height values within a search window with appropriate size. The size of the window has to be chosen such that it is larger than the expected minimum building size known from prior information.

The generation and verification of building hypothesis is performed once the terrain and non terrain segments are identified. Connected component labeling is computed to group non-terrain segments. Buildings that have size lower than a predefined threshold, a prior knowledge based on buildings' size and shape, are rejected.

To reconstruct buildings, Morgan and Habib (2002) determine three dimensional internal building break lines and the building boundary.

The estimation of 2D boundary is done by detecting straight lines that fit the centers of the bounding triangles created with the points located inside and outside the building (Figure 2.2). The fitting process is carried out by means of Hough transform. The latter is used to detect straight lines based on the 2D coordinates of the centers of the bounding triangles. Intersecting the detected lines will delineate the building boundary.

Real laser data with a point density of 1.5 points per square meter has been used to test the proposed method. An example of the results obtained is provided in figure 2-3. A ground truth in the form of 2D GIS layer has been used to evaluate the results. The experiments performed show successful results. But the authors recommend the use of constraints such as parallelism and perpendicularity or the procurement of the building boundaries from other sources such as aerial photos. Due to the small number of bounding triangle centers along the short boundary lines, the 2D outline has not been correctly reconstructed. As claimed by the authors, the larger the laser point density, the higher the success of extracting the boundaries in terms of accuracy and certainty.

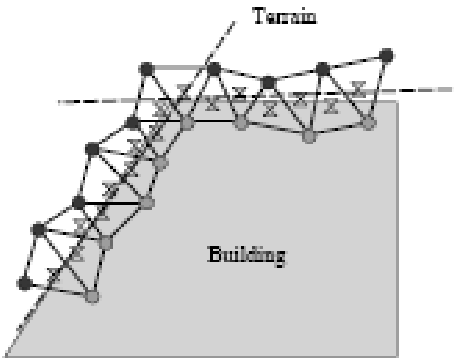


Figure 2-2: Estimation of Building Boundary, [Morgan and Habib, 2002]

The use of normal vectors during the segmentation procedure is not recommended by many researchers as it introduces some errors. Indeed, as explained by Alharthy and Bethel (2004), normal vectors tend to be very noisy due to the variability in the lidar points. As shown by figure 2-3, the extracted boundary is too much generalized compared to the ground thruth.

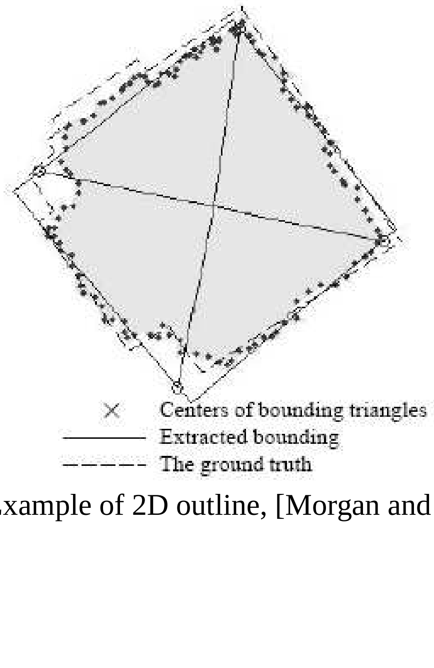


Figure 2-3: Example of 2D outline, [Morgan and Habib, 2002]

2.2.3. [Alharthy and Bethel, 2002]

The objective of this research is to design a fast, efficient and low cost algorithm for the extraction of 3D features in urban areas. To avoid the limitation of availability of other sources of information such as ground plans, imagery and multispectral data, only the raw lidar data has been used as a range image.

The aim being to detect and reconstruct buildings in dense urban areas, the first step was to filter the data in order to identify candidate building points from other urban features. To remove extraneous objects such as trees and any other object above the ground that does not belong to the building category, two techniques have been applied successively: first and last pulse return analysis and local statistical variation.

The laser pulse is not a single ray but a cone of light. Therefore it has the ability to capture several returns per each height point. By comparing the first return height minus the last return height to a given threshold, buildings are isolated and most of the tree regions are removed. But some noises are not cleaned.

A second filtering approach based on local statistical analysis and interpretation is introduced. The principle applied is based on a moving square window where a root mean square error of the variations in height is used to classify the point in the middle of the window. In this process, low variation of height is an indication of smooth surfaces while high variation indicates the presence of irregular surfaces, characteristic of tree regions. High variability surfaces are detected and filtered.

The result of the filtering process is a DSM which represents only terrain and buildings. Before the delineation of building footprints, a normalized DSM is created by subtracting the DEM from the filtered DSM. To remove remaining undesired small objects like cars, a local minimum filter is applied with a threshold based on minimum objects' height and size. This information is obtained from prior knowledge on buildings.

The second step in the process is the reconstruction of building polygons using the extracted raster building footprints. Buildings are constrained to have two dominant directions perpendicular to each other. To convert a building footprint into regular vector connected line segments, the procedure is run as follows:

- Dominant directions are estimated using image cross-correlation. This is achieved by computing the histogram of all line segments orientations. The two angles perpendicular to each other with the highest frequencies are used as dominant directions;
- building footprints are rotated to have horizontal-vertical bearing;
- line segments are extracted with the constraint of having one of the two dominant directions;
- extracted line segments are connected to each other;
- Histograms of the boundary points are used to generalize line directions and positions. Indeed, boundary points within a limited spacing are clustered at the maximum coordinate;
- Buildings polygons are rotated to their original orientation.

An example of the results obtained is provided in figure 2-4.

The approach has been tested on the data collected over the Perdue university campus in 2001 with an approximate density of one point per square meter. The performance of the filtering step is excellent though it's the most time consuming step. The determination of building polygons shows satisfactory results.

This paper lacks of a rigorous evaluation of its results. In addition to the use of range image which involves interpolation and therefore introduction of errors, buildings are forced to have two dominant directions which is not always the case in reality.

Figure 2-4: Example of 2D outline, [Alharthy and Bethel, 2002]

2.2.4. [Alharthy and Bethel, 2004]

Alharthy and Bethel (2004) elaborate a methodology for the reconstruction of buildings from airborne laser data using a moving surface method. Firstly, geometric parameters for moving surfaces are estimated. These parameters are then used to segment the lidar data into planar roof facets. The next step is the extraction of plane roof polygons.

To estimate the geometric parameters of roof faces (slope in x, slope in y and height intercept), a least squares moving surface analysis with variable window sizes and shapes is determined. In other words, a grid is overlaid on the irregular laser points and a least square adjustment is performed within each window to determine the parameters of the plane that fitted the best to these points. The RMSE of the fitted data is computed as well. The RMSE indicates how well the estimated plane fit to the Lidar points.

Using the parameters estimated in the previous step, the roof planar segments are extracted based on a region growing algorithm starting with a seed region. Thus neighboring pixels are examined and added to the region if they have common characteristics. As a result of this step, roof facets are segmented and labeled.

In this paragraph, the procedure of translating roof facet regions into vectorized polygons is discussed. To extract plane roof polygons, Alharthy and Bethel (2004) propose two methods. The first, designed for simple roof structures is based on the approach described in Alharthy and Bethel (2002). By simple roof structures, the authors mean that breaklines between roof segments are parallel to one of the two dominant directions of the building footprints. This algorithm maintains the squaring property of the extracted polygons and includes intermediate steps such as line extraction, connecting, trimming and polygon formation.

For the complex roof segments where the breaklines are supposed to take any direction, the approach considered treats each region individually. After sorting the points in a clockwise mode, unnecessary ones are eliminated using their altitude and a fixed threshold. To increase the probability of keeping corner points, the altitude is divided by the base of the appropriate triangle.

An example of the results obtained is provided in figure 2-5.

According to the authors, the developed methods provide satisfactory results with a dataset that is not dense (one spot height per square meter). More dense data might improve the roof details. But the segmentation procedure might fail for regions not large enough to contain an appropriate number of points. Another example of segmentation failure occurs when adjacent trees cause an occlusion where not all pulses can reach the building roof. The performance of the algorithm deteriorates in the presence of objects close by the roof regions. The algorithm designed for polygons extraction show a good performance. However, some nodes might be shifted from their true position during the adjustment procedure.

A quantitative performance analysis has not been made in order to appreciate how good the results are. But as said by the authors, the main goal of this work is to test the suitability of lidar data for roof reconstruction rather than reconstructing with great precision building outlines.

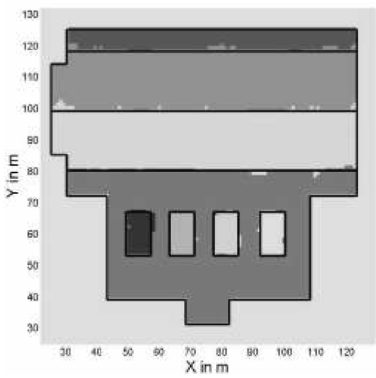


Figure 2-5: Example of 2D outline, [Alharthy and Bethel, 2004]

2.2.5. [Clode et al, 2004]

Clode et al (2004) develop a new method using the multi-echoes property of the laser beam to determine building outlines. The idea is to use the points that are identified as building edge points to accurately delineate the building outlines.

They first step is to segment the aerial laser data into building, terrain and building edge points. For this purpose, an initial classification is performed using the normalized digital surface model. The last pulse laser points are used to create a last pulse DSM. A mathematical morphological gray scale opening with various structural elements is then performed to create a coarse DTM from the DSM previously obtained. From the difference of DSM and DTM, a building mask is obtained. An edge point mask around the perimeter of the building is created by removing pixels inside buildings. To avoid misclassifying neighboring trees and eliminating many edge points, an appropriate width of the outline band has to be chosen. All last pulse points inside the mask are classified as buildings points and those lying outside are terrain points. Points lying precisely on building edges can then be isolated.

The algorithm detects from the outer points the ones that are likely to belong to the building boundary. The idea is to position the outline at the required place. The points that lie on building edges can be detected using the multi-pulse returns property of the laser beam. Indeed, when a laser beam hits the border of a building, some of the energy of the laser beam is reflected from the top of the building (Figure 2.6). The remaining part of the energy is reflected from the ground or objects at lower altitude. Thus a first pulse return point among multiple pulse return points is a boundary point when dealing with buildings. The remaining points from the outer points are near the building boundary but they are not part of the border.

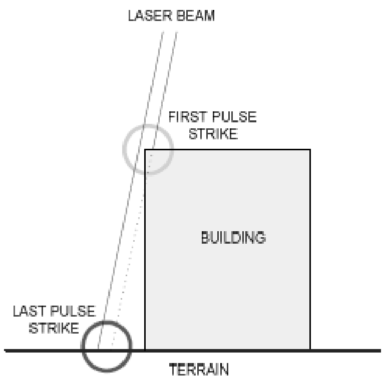


Figure 2-6 : Multi-pulse property of the laser beam, [Clode et al, 2004]

To supplement airborne laser scanner points lying on building boundaries, interpolated edge points are determined by performing a Delaunay triangulation between points classified as terrain and building points.

A building consists of a series of straight-line segments. Each identified edge point is allocated to one of these segments. A weighted least square adjustment is computed to calculate position and direction of each edge line segment. The extents of the segments are determined by intersecting adjoining segments.

To allocate points to line segments, the points are first arranged in a circumnavigated manner. A circle of ‘construction points’ and centered on the centroid of the building is determined. This bounding circle is used to detect provisional corners by computing for every building the histogram of the number of ‘construction points’ that are furthest to every boundary point. The highest three peaks are identified as provisional corners. From there, an iterative process is then computed to find eventual additional corners and to allocate building points to edges.

After points are assigned to line segments, maximum likelihood estimation is used to compute edges' orientation. The position of the edge is determined by a weighted mean of all allocated points. The weights are proportional to the inverse of the squared standard deviations which are computed using the flying height, the divergence of the laser data and interpolated distance between points classified as terrain and building. The final outline is made of an ordered list of locations computed from the intersection of estimated lines.

An example of the results obtained is provided in figure 2-7.

In most cases according to the authors, the algorithm performs as expected but the research is still in progress. Improvements of the results are expected with the increase of the point density. Other problems encountered by the authors are the shadowing effect and the dead time of the laser scanner system which both cause some lack of data.

Based on the illustrations provided in the paper, further effort are indeed required to make this algorithm robust. The boundaries are not delineated accurately and furthermore, no prior knowledge related to buildings shape has been used. Consequently corners likely to have right angle do not.

Figure 2-7: Example of 2D outlines, [Clode et al, 2004]

2.2.6. [Wang, 2006]

To extract building boundaries, Wang (2006) designs an algorithm with a series of steps that together form a semi-automatic process. The acquired laser data is classified segmented and finally the footprints are extracted.

The automatic classification of data points has been carried out with the software AdaBoost. For sake of simplicity, the original point cloud is resampled onto a regular grid using nearest neighbor interpolation method. The dataset is classified into three different classes, naming buildings, trees and grass. For this purpose, four parameters have been considered: height, height variation, normal variation and Lidar return intensity. A manually created training sample is used by the AdaBoost algorithm to perform the classification on the whole dataset pixel by pixel. The set of points classified as buildings is used as input for the following step.

Building segmentation is performed in three different steps: grouping building regions, removal of small buildings and removal of tree regions or regions misclassified as buildings. The principle used is a region growing algorithm starting with a seed region. The grouping criterion is based on a 2D Euclidian distance. To reduce systematic errors from previous step, a post processing step is carried out. Thus a cluster is discarded if its size is less than the minimum specified by the user. Tree regions are removed when the ratio of points with multiple returns to single returns is high.

To extract building footprints, the first step is to detect the boundary points. This is done by using a local neighborhood search. The idea is that a point on the boundary should have a large region in a direction where no other point exits. When a gap of 70^o is found, the point is considered to lie on the boundary. This algorithm could miss some boundary points, which is not a problem as this step intends only to find a rough outline.

A first approximation of the footprint is performed by ordering the candidate points and tracing a path between neighboring nodes until the starting point is reached. This approximated outline could contain non-desired right angles. In order to prevent local level noise from affecting the convergence of the minimization problem during the regularization process, the principle of shortest path is applied. To achieve this objective, the algorithms of Dahl and Realfsen and the one of Floy-Warhall are used. The idea is to replace a sequence of edges by a single edge with an error less than a predefined threshold. The result obtained from this step is an approximated outline that has a minimum number of sides.

In this final step, the previous outline is regularized. Prior knowledge related to buildings such as straight edges and right angles are considered. For this purpose, a Bayesian Maximum a Posterior estimation is computed. The idea is to determine all possible outlines and calculate their probability of being the best to fit to the data with building constraints applied. The probability function combines the goodness of fit to the data measured by the distance from the boundary point to the polygon with a prior on footprint shapes which is function of the polygon's angles that encourages straight lines, 90^o, and to a lesser extent 45^o and 135^o. The required outline is the one with the highest probability. During the optimization process, simulated annealing is used to help avoid local minima. Simulated annealing is an algorithm applied to locate the global optimum of a given function.

In this methodology designed by Wang, (2006), some strategic boundary points could be missed when looking for the outer points. The principle of local neighborhood search used to determine the first approximation of the outline is inadequate. See examples of the results in figure 2-8. From these examples, it can be noticed that only simple buildings are considered.

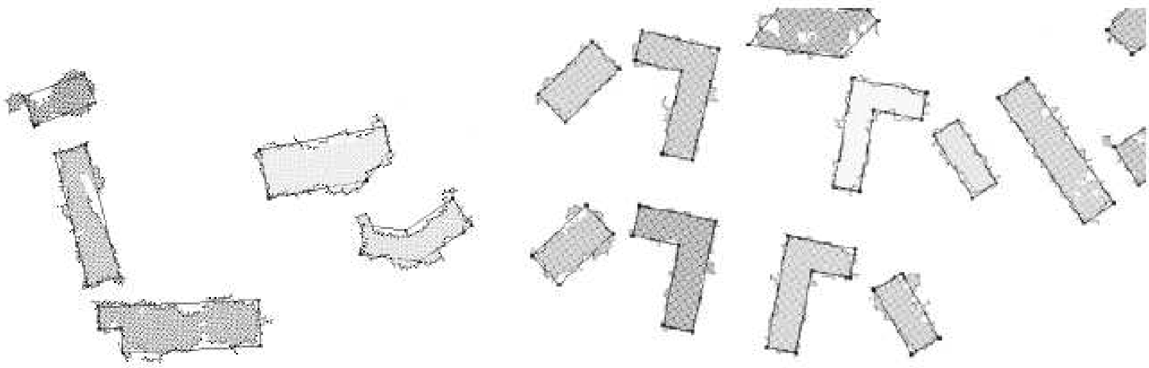


Figure 2-8: Example of 2D outlines, [Wang, 2006]

2.3. Techniques using raw point clouds exclusively

The techniques presented here work on the original laser scanner data without the requirement of an interpolation to a regular grid.

2.3.1. [Vosselman, 1999]

Vosselman (1999) proposes a new method for building reconstruction using planar faces in very high density height data. The process starts with the determination of planar faces, which is followed by the model reconstruction.

In this algorithm, the author assumes that building models can be described by planar faces. In addition, assumption is made that the outlines are polyhedral objects and their edges are either parallel or perpendicular to the main building orientation. This latter is obtained from the direction of the horizontal intersection lines between the roof faces.

The determination of planar faces is based on clustering points into planes.

The first approximation of the 2D building outline is made of the outer edges of the irregular triangulation network obtained after the connected component analysis of the segmented planes. The contour is then regularized with straight lines by the means of a sequential algorithm making use of least squares adjustment. The first two points are used to define a line that is updated based on the following points in such a way that the distance of a point to a line doesn't exceed a given threshold. The next line starts from the last point of the previous line in a perpendicular direction. After all points are processed, their assignments to line segments are reconsidered in order to reduce the square sum of the distances of the points to the lines. The outline is further improved by the elimination of very short edges (An example of the results obtained is provided in figure 2-9).

This algorithm provides good results. The increasing point density and the avoidance of height interpolation clearly improve the determination of building outlines. The accuracy assessment of this algorithm has been analyzed by superposing the reconstructed outlines on existing aerial photographs. From this evaluation, different conclusions are derived:

- The different errors noticed are directly linked to the low point density. Higher point spacing will provide better results.
- The use of least squares adjustment with the constraint that 80% of the contour points must fall within the building outline causes an underestimation of the size of the buildings.
- Vegetation next to buildings cause some errors in the determination of the building outline

In order to improve the designed algorithm, some recommendations have been made:

- the incorporation of the laser beam width and the percentage of the energy reflected by the roof surface;
- The use of constraints such as collinearity and symmetry. Enforcing such constraints will provide more regular shapes.

It is also suggested the use of ground plans when they are available and when the objective is not to determine roof edges but the building footprints. Also, to reduce the large number of thresholds needed, statistical reasoning such as minimum description length is recommended. Another suggestion of the author is the manual editing to correct for the different errors observed.

In addition to the low point density, this algorithm suffers from the fact that all angles of a building outline are made right, which is not always the case in real situation.

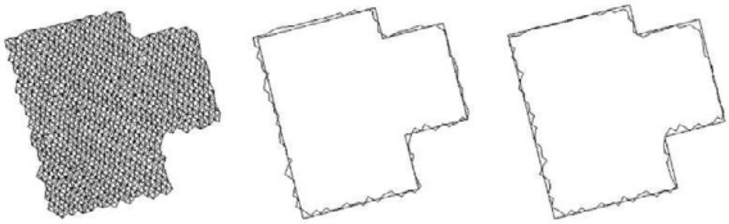


Figure 2-9: Example of 2D outlines, [Maas and Vosselman, 1999]

2.3.2. [Cho, Chang and Lee, 2004]

Cho, Chang and Lee (2004) propose a practical method for building detection and extraction using airborne laser scanning data. The particularity of this approach is the introduction of concept of Pseudo-Grid Based Building Extraction. Three main reasons that justify this new concept are to avoid loss of information and accuracy due to interpolation, to define adjacency of neighboring laser points and to speed up processing time. The process which has been divided into low-level and high-level steps is made of pseudo-grid generation, noise removal, segmentation, grouping for building detection, linearization and simplification of building boundary. Each of these procedures changes the domain of input data such as point and pseudo-grid accordingly in order to provide efficient data processing.

In the low-level process, a pseudo-grid is generated using the average point density. Lidar points are then assigned to each of the grid's voxels. By a statistical method, irregular random errors contained in the raw laser point data and generated from instrument malfunction are removed. The following step is the application of local maxima filter to segment the data and then to extract boundary candidate points.

The high-level process is made of grouping laser points, tree removal and extraction of building boundary. Grouping points per building is performed in the pseudo-grid domain. To remove trees, the concepts of minimum building area and circularity are used. However some trees couldn't be eliminated. Building boundary extraction is performed in both point and pseudo-grid domain. For each group, the boundary is computed and linearized. Finally, it is simplified by extracting interest points corresponding to building corners (An example of the results obtained is provided in figure 2-10).

The proposed approach has been tested on lidar data acquired for the city of Chungjoo in Korea.

In addition to the fact that no accuracy assessment has been performed, this paper suffers from the lack of detailed explanation on the different techniques applied. Instead of focusing on the improvement of the outline accuracy, this paper intends to improve the processing time. Also, as explained by the authors, some errors found in the results are generated from the misclassification of some trees into buildings. Thus, the methodology applied for classification requires further work.

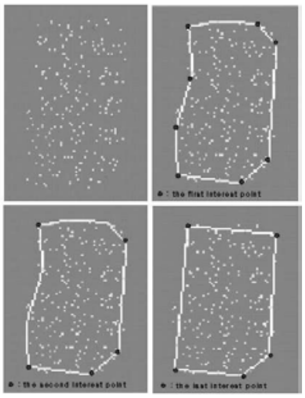


Figure 2-10: Example of 2D outlines, [Cho, Chang and Lee, 2004]

2.3.3. [Sampath and Shan, 2007]

Sampath and Shan (2007) design a new procedure for tracing and regularizing building boundary from airborne lidar points. The algorithm is performed in four different steps: separation of building and non-building lidar points, segmentation of lidar points that belong to the same building, tracing of building boundary and regularization of the boundary.

As a prerequisite for building segmentation, the raw lidar points have to be classified into building and non-buildings points. This objective is achieved by using the filter proposed by Sampath and Shan (2005). It is a slope based one-dimension and bi-directional algorithm. The idea is to create a lidar profile and to classify points between a large positive slope and a large negative slope as non ground points.

The task in the segmentation process is to find points that belong to an individual building. This is achieved by a region-growing approach. The main property used is the uniformity in the distribution of points within a cluster. It is an iterative process which uses a moving window oriented along and perpendicular to the scan directions. The process ends with the removal of small segments likely to represent trees or cars not rejected from the filtering process.

Boundary tracing is then performed with the use of a modified version of the convex hull algorithm proposed by Jarvis (1977). The convex hull or convex envelope for a set of points is the minimal convex set containing all points. In other words, the convex hull is the smallest convex boundary containing all the points. In the modified version of the convex hull formation algorithm, the search of the next point is made in a rectangular neighborhood of the current point. The algorithm starts by determining the left most point and ends when a determined boundary point happens to be the left most point. A boundary point is found, when after having selected neighboring points of the previous boundary point, the clockwise angles between previous, current and candidate points are computed and the point corresponding to the least angle is chosen.

Finally, the boundary is regularized by a hierarchical least squares adjustment. Indeed, due to the irregular distribution of lidar points, the traced boundary appears ragged. To carry out the boundary refinement, the first step in the regularization step is the classification of points lying on longer lines segments based on the difference in slope of two consecutive edges. These segments modelled by a line equation, are sorted in two groups based on their slope. The next step is to determine a least square adjustment where these lines are either parallel or perpendicular to each other. In the final step, a global least square adjustment is performed including all line segments. The previously determined values are considered as weighted approximations and no explicit constraint is enforced at this level.

Some examples of the results obtained are provided in figure 2-11.

The designed approach has been tested on three different sites with different point spacings. Orthoimages of the target cities have been used as independent reference data. From the superposition of the reconstructed outlines with the orthoimages, some appreciations have been made. In addition, numerical quality-assessment of the least square adjustments has been performed. It can be concluded that almost all building edges are well determined. But due to the limited resolution of the lidar data, some details are missed and artefacts are introduced. Very low places of building may be identified as ground, which cause missing parts in the regularized building. The evaluation reveals that right angles formed by short edges may not appear in the regularized buildings. It has also been found out that the maximum distance between a lidar point and its corresponding line segment is proportional to the point spacing. Further effort are required to extend the presented approach to handle buildings with multiple and non-perpendicular dominant directions.

The method of Sampath and Shan, (2007) provides good approximated outlines. But, as said by the authors, further effort is required to improve the hierarchical adjustment proposed in the regularization step by considering buildings with not necessarily right angles.

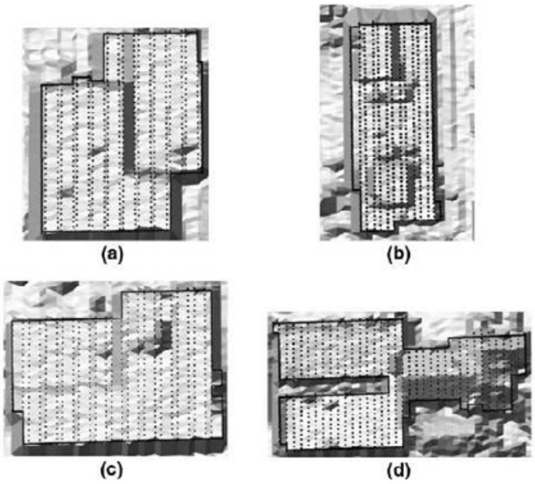


Figure 2-11: Example of 2D outlines, [Sampath and Shan, 2007]

2.4. Techniques using other information sources

2.4.1. [Gerke et al , 2001]

Gerke et al (2001) extracts 2D roof outlines of buildings from aerial imagery using Invariant Geometric Moments. The advantage of using moments is that they directly lead to the five parameters (width, length, orientation and position in x and y) describing a rectangle around the region. The use of invariant moments to extract building outlines was also experienced by Maas and Vosselman (1999). The whole process subdivided into detection of building areas and reconstruction of outlines is embedded into a generic scene model.

To detect building areas, a hierarchical scene model is used to classify the image with the help of context-dependant knowledge. The authors also make use of normalized DSM. Thus, domains that have a low NDVI and contain 3D object are considered as building areas.

Buildings are then detected in building areas and individual building outlines are reconstructed. For building areas containing shadow regions, a histogram is computed where the left main peak representing the shadow information is used to remove undesired regions. To reconstruct the outlines assumed to be orthogonal closed polygons, the approach used is based on invariant geometric moments which provide rectangle outlines. As complex buildings cannot be described by single rectangles, a process called decomposition is carried out where undesired areas are modelled by rectangles and subtracted from initial outline.

Two problems observed with this methodology are highlighted by the authors: the reconstruction of nearly quadratic building which fails with the present process and the miss-orientation of the initial rectangle. For the latter, a solution has been found to rotate the initial rectangle until the area covered by this rectangle and the building region becomes a maximum.

To test the method, an image having a ground sampling distance of 10cm has been used together with a DSM whose resolution is 20cm. While some interesting results have been obtained, some shortcomings are observed due to the miss orientation of initial buildings, the non-robust shadow removal process and the fact that not all buildings have orthogonal outlines. Some examples of the results obtained are provided in figure 2-12.

As proposed by the authors, further work is required to make this algorithm robust. It should be considered another alternative than the invariant moments for the determination of the main orientation of the roof outline. Also, cases where outlines are not right shaped should be investigated.

Figure 2-12: Example of 2D outlines, [Gerke et al, 2001]

2.4.2. [Sohn and Dowman, 2003]

Sohn and Dowman (2003) design an automated method to extract building outlines using lidar DEMs and Ikonos images. Although a lot of photogrammetry research has focused on the reconstruction of building boundaries, the design of this new technique can be justified by two main reasons. First the low contrast, occlusion and shadow effects on images in high density urban areas make it difficult to extract features. On the other hand, according to the authors, lidar data solely used, even with high density of points, cannot delineate accurately building boundaries.

The fist step of this process is to localize individual buildings with a rectangle polygon by means of a hierarchical segmentation of lidar DEM and Ikonos multi-spectral information. The algorithm used here is the one developed by Sohn and Dowman (2002). The lidar DEM is fragmented into a set of homogeneous sub-regions where the underlying terrain is characterized by a single slope. Thus it is easier to distinguish between on-terrain and off-terrain points. An individual elementary terrain named planar terrain surface (PTS) is classified as planar terrain if the heights of point inside this triangular area are within a given threshold; otherwise it is fragmented into pieces by a Delaunay triangulation until the latter are verified as PTS. Reliable off-terrain points belonging to buildings and trees are obtained by removing outliers based on a simple threshold. The differentiation between building objects and trees is made by the use of Ikonos multi-spectral bands. Finally, a connected component labeling process is applied creating blobs represented by rectangle polygons.

The second step in which buildings are extracted is made of three different sub-processings naming intensity line cue generation and filtering, virtual line cue generation and polygon cue generation and grouping.

Intensity lines meaning lines based on color information are extracted from Ikonos imagery by the Burns algorithm [Burns,1986]. Extraneous line segments are filtered by a length criterion.

In order to compensate the insufficient density of intensity line cues, virtual line cues are extracted from lidar data. The main assumption considered here is the fact that building shapes are made in some degree of geometric regularity. But this is used as a weak constraint as polyhedral buildings may not have symmetric property. The use of virtual line cues in boundary representation is subject to the degree of complexity of individual buildings.

From the intersection of intensity and virtual cue lines, convex polygons are generated. The boundary representation is reconstructed by a collection of building polygons. For that purpose, the Binary Space Partitioning (BSP) method developed by Fuchs, Kedem and Naylor (1980) is modified considering the contribution of lidar data. This tool is used for a recursive partitioning of regions by hyperlines in 2D image space. Some examples of the results obtained are provided in figure 2-13.

The building extraction method described in this section has been tested over a site of Greenwich industrial area in London. An Ikonos Pan sharpened image with one meter resolution was used. In addition, lidar points were acquired over the test area by OPTEC airborne laser scanner with a point density of 0.09 points/m2. From the results obtained, it can be noticed that most buildings shapes are properly reconstructed by linear features. However, the technique suffers from several difficulties. Most residential houses failed to be localized due to low density of lidar data and its uneven distribution. In addition, the algorithm makes use of a relatively high number of parameters.

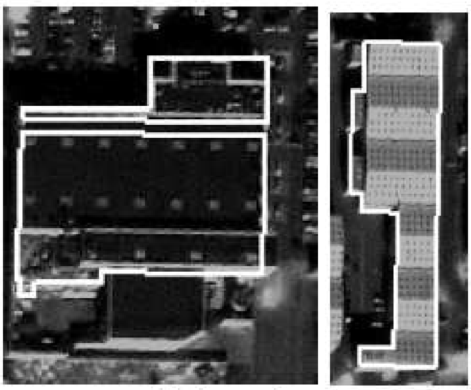


Figure 2-13: Examples of 2D outlines, [Sohn and Dowman, 2003]

2.4.3. [Lafarge et al, 2006]

Lafarge et al (2006) design a fully automatic building footprints extraction method from Digital Elevation Models. It is an object-oriented procedure where building footprints are extracted from the DEMs based on marked point processes. The method allows the use of a priori knowledge and doesn't need localization maps.

The first step consists in generating DEMs which is the altimetric description of urban areas from 3 view-images. The images have a sub-metric resolution with a high stereoscopy. The method applied to achieve this objective solves the surface reconstruction problem by formalizing it as a minimization of energy.

In the second step of the process, the extraction of building footprints is made using the marked point processes. It consists of generating simple geometric objects (rectangles) as building outlines. A marked point process is a set of points represented by their 2D coordinates associated with a rectangle determined by its orientation, length and width. A density function is defined which integrated three different energies, naming external energy, internal energy and exclusion energy. The external energy measures the quality of the rectangle given the DEM. The idea is to extract some points and to check the coherence between these points and the rectangular shape of the object. The internal energy allows giving a spatial structure to the configuration. The exclusion energy avoids redundant objects by penalizing the intersection of parallel rectangles. The global minimum of this energy is found by applying a Reversible Jump Monte Carlo Markov Chain sampler embedded in a simulated annealing scheme.

In the last step of the determination of 2D outlines, boundaries are regularized towards structured footprints. In other words, neighbouring rectangles are connected to create a structured polygon. An exhaustive description of all the fusion configurations will be very heavy. Therefore, only most realistic cases have been considered. In order to select the most adapted configuration, a cost function has been defined. The latter is composed of three terms: the DEM cost, the recovering cost and the contour cost. The first cost defined by the rate of pixels inside the proposed footprint is supposed to define the quality of the proposed configuration, given the DEM. The recovering cost is computed by using the surface of the proposed configuration with the surface of the two initial rectangles. Instead of surfaces, the contour cost considers the lengths of the features. The most adapted fusion configuration is the one with the least value for the cost function.

The methodology has been applied in the determination of 3D-city modelling using PLEIADES simulations from the future PLEIADES satellites. The results are satisfactory. However, two drawbacks have been encountered. Low flat buildings have not been identified as they present low DEM discontinuities. Secondly, some trees have been detected as buildings but this can be corrected by introducing a vegetation mask.

In the final outcome of this method (See examples in figure 2-14), intermediate line between two neighbouring rectangles glue together are still visible. No quantitative analysis of the accuracy assessment has been made in order to appreciate how precise is the final product.

Figure 2-14: Example of 2D outlines, [Lafarge et al, 2006]

2.4.4. [Dutter, 2007]

Dutter (2007) develops a method for generalization of building footprints derived from high resolution remote sensing data. The idea is to create simple polygons with right angles whose degree of details is function of parameters provided by the users.

This algorithm requires some prerequisites, one of which is that the Euclidian distance between two successive points in the outline should be similar. The first step in the process is to check whether this criterion is met. If it is not the case, additional corners are added. The following step is the computation of the main orientation of the building outline which is taken from the orientation of the longest edge of the minimal bounding rectangle (MDR). To determine the MDR, a built-in function in ArcMap is used to calculate the convex Hull of the polygon. The MDR is the rectangle with the smallest area having one side collinear with an edge of the convex hull.

Different levels are then considered in the determination of the outline. At level one, the process approximates the building outline with a simple rectangle. If the rectangular model doesn't fit well enough the dataset, additional corners, the so-called new split-points are computed. This leads to Level 2 where buildings are expected to have L, T or Z shape or level 3 where the U-model is considered. The points are then assigned to every edge and the position of the edge is calculated with respect to the corresponding MDR-edge. Finally, short edges are removed. In case the outline obtained is not satisfactory enough, tools have been developed for manual editing.

To implement this process, a generalization tool has been built in ARCGIS. The data used for the practical demonstration contains 315 buildings. Some examples of the results obtained are provided in figure 2-15.

Three parameters have been defined to measure the quality of the outlines:
- The orthogonal distances between points along original polygon and the generalized polygon.
- The Hausdorff distance which is a measure of the degree of mismatch between two sets. It is defined as the maximum distance between the two sets.
- The area of symmetric difference which is the sum of areas that are whether in the original or generalized outline but not in both. The greater the symmetric difference, the worse is the result obtained.

After having evaluated the presented algorithm, it turns out that the concept of split points to find a suitable model for an arbitrary building polygon provides good results. 88.3% of buildings have been automatically generalized. From all polygons 3.2% have a bad generalization quality, but remain undetected by the built-in quality check. Due to the coarse orientation error, 5% of the buildings are generalized inaccurately.

Some limitations have been noticed. These include the limited geometry of the generalized polygon (only right angles) and the determination of the main orientation based on the MDR which fails in some cases and lead to a wrong outline.

Figure 2-15: Example of 2D outlines, [Dutter, 2007]

2.5. Some polygon reduction techniques

The purpose of polygon reduction techniques is to reduce the number of points of the polygon, without changing the main characteristics of the polygon.

2.5.1. Vertex reduction algorithm

In vertex reduction algorithm, successive vertices that are clustered too closely are reduced to a single vertex. For this algorithm, a polyline vertex is discarded when its distance from a prior initial vertex is less than some minimum tolerance. Specifically, after fixing an initial vertex V0, successive vertices Vi are tested and rejected if they are less than ε away from V0. But, when a vertex is found that is further away than ε, then it is accepted as part of the new simplified polyline, and it also becomes the new initial vertex for further simplification of the polyline. This procedure is easily visualized in figure 2.16.

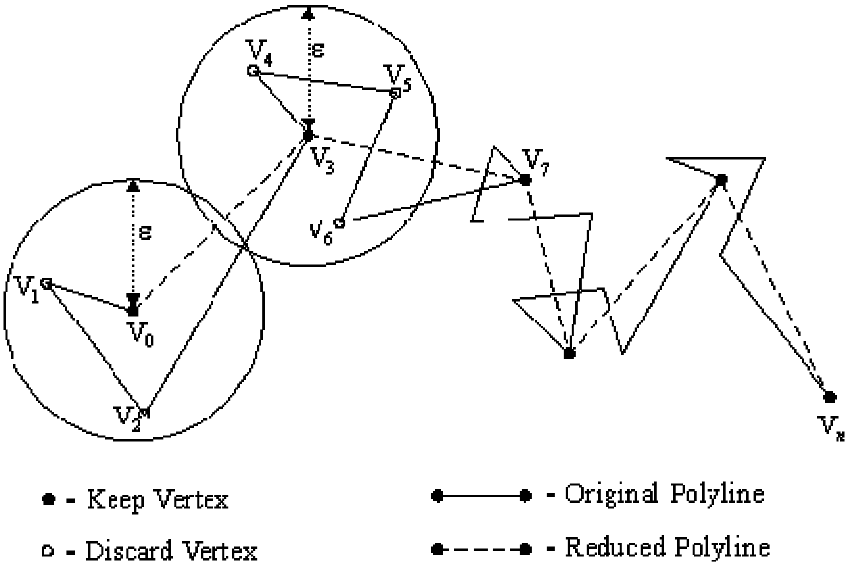


Figure 2-16 : Vertex reduction principle,

[http://geometryalgorithms.com/Archive/algorithm_0205/], (Accessed in November 2007)

2.5.2. Douglas-Peucker Algorithm

Whereas vertex reduction uses closeness of vertices as a rejection criterion, the Douglas-Peucker algorithm uses the closeness of a vertex to an edge segment. This algorithm starts by considering the single edge joining the first and last vertices of the polyline. Then the remaining vertices are tested for closeness to that edge. If there are vertices further than a specified tolerance, away from the edge, then the vertex furthest from it is added to the simplified polygon. This creates a new guess for the simplified polyline.

This procedure is repeated recursively. If at any time, all of the intermediate distances are less than the threshold, then all the intermediate points are eliminated. Successive stages of this process are shown in (figure 2.17).

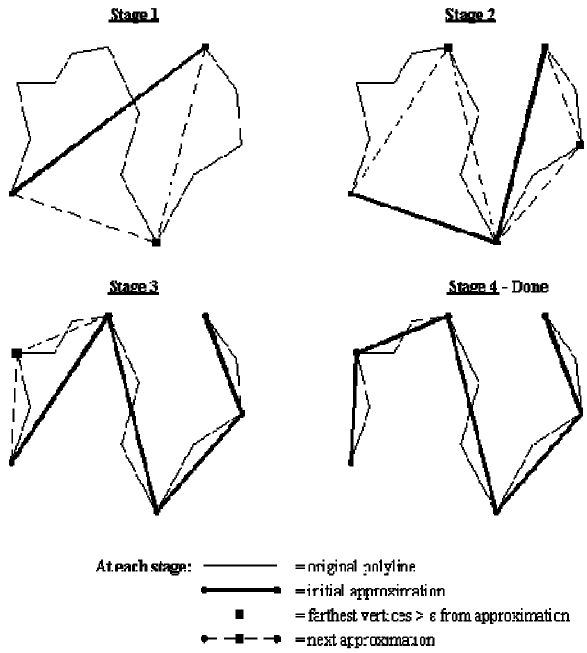


Figure 2-17 : Douglas-Peucker Principle

[http://geometryalgorithms.com/Archive/algorithm_0205/], (Accessed in November 2007)

2.5.3. Discussion

These generalization methods are not adapted for 2D building outline reconstruction. Indeed, the output of these techniques is a set of points extracted from the initial dataset which do not necessarily represent building corners that sometimes have to be computed. In addition, joining these points will not necessarily provide the squaring property of buildings.

2.6. Summary

A summary of the above survey is provided in the tables 2-1, 2-2 and 2-3.

Table 2-1: Summary of techniques for reconstruction of 2D building outlines (Techniques using range images exclusively)

Order	Research	Identification and Extraction of building segments	Determination of initial outline	Regularization of outline
1	[Weidner and Förstner, 1995]	Normalized DSM + connected components + removal of noise	Vectorization of building segment outline	Minimum Description Length
2	[Morgan and Habib, 2002]	TIN + Region growing with the use of surface normal vectors + morphological filter +	Bounding triangles created with points located inside	Hough transform for the detection of straight lines + intersection of these

		Connected components	and outside the building's domain	lines.
3	[Alharthy and Bethel, 2002]	First and last pulse return analysis + local statistical variation + Normalized DSM	Vectorization of building segment outline	Image cross-correlation to detect two dominant directions perpendicular to each other
4	[Alharthy and Bethel, 2004]	Normalized DSM	Vectorization of building segment outline	Sort points and eliminate unnecessary ones
5	[Clode et al, 2004]	Normalized DSM	multi-echoes property of the laser beam + Delaunay triangulation	Weighted least square adjustment + Maximum likelihood estimation to compute edges' orientation+ Least squares adjustment to compute position
6	[Wang, 2006]	AdaBoost algorithm using nearest neighbor interpolation method + segmentation	local neighborhood search	Bayesian Maximum a Posterior estimation + simulated annealing

Table 2-2: Summary of techniques for reconstruction of 2D building outlines (Techniques using raw point clouds exclusively)

Order	Research	Identification and Extraction of building segments	Determination of initial outline	Regularization of outline
7	[Vosselman, 1999]	Detection of planar faces + Connected component analysis	2D Delaunay triangulation	Least squares adjustment
8	[Cho, Chang and Lee, 2004]	Local maxima filter	Linearization	Simplification
9	[Sampath and Shan, 2007]	One-dimension and bi-directional height profile + region-growing	Modified version of Convex Hull	Hierarchical least squares adjustment

Table 2-3: Summary of techniques for reconstruction of 2D building outlines (Techniques using other information sources)

Order	Research	Identification and Extraction of building segments	Determination of initial outline	Regularization of outline
10	[Gerke et al , 2001]	Normalized DSM	Invariant Geometric Moments	Process of decomposition where undesired areas modelled by rectangles are subtracted from initial outline.
11	[Sohn and Dowman, 2003]	Hierarchical Segmentation + Delaunay triangulation + Connected Component Labeling	rectangle polygon + intersection of intensity and virtual cue lines	
12	[Lafarge et al, 2006]	Normalized DSM	Marked point processes	Bayesian Maximum a Posterior estimation
13	[Dutter, 2007]	-	Convex Hull	Multi-level algorithm with a built-in quality check running from simple rectangle to more complicated shape

2.7. Is there a need to develop another algorithm?

All the approaches listed in this survey provide results with shortcomings (intrusions, extrusions and edges not properly delineated, non right angles not taken into account…). The 2D outlines obtained are not satisfactory enough according to the authors who suggest further research on the topic. Two main reasons justify the problems encountered by researchers: the data used and the methodology.

Indeed, one of the common difficulties highlighted by most of the researchers is the low point density. The datasets used for the implementation of the methods runs from 0.1 point per square meter [Sampath and Shan, 2007] to 7 points per square meter [Vosselman, 1999]. There is a need to use a data with a higher point density in order to get better results.

The second problem faced by most of the researchers is the methodology used in the regularization of the building boundary. The processes for the elimination of unnecessary corners and the determination of the final directions of the building edges are partly responsible of the shortcomings noticed in the results. The different algorithms designed for the determination of the main orientation of the outline are not robust. An improvement is required for all these approaches.

Another weakness of most of these papers is the lack of a quantitative analysis of the accuracy assessment. To which extent the determined 2D outlines are accurate is not clearly explained in most of the papers. Those who try to analyze quantitatively the results obtained didn't use some reference data but rather they rely on parameters defined using the raw point clouds and the computed outlines. These indicators are not enough to evaluate the quality of the outlines.

Knowing the advantages of automating the generation of 2D building outlines, there is a need to improve existing methods or to design a new one by taking advantages from what has already been done. In the new approach, a data with a higher point density and a better process of reshaping the approximated outline have to be found. This is the objective of the following chapter.

3. Proposed approach for the determination of 2D building outlines

This chapter starts with the definition of an outline which is followed by the strategy that is used to determine it.

3.1. What is a 2D building outline?

In this research, 2D outline means the 2D boundary of a building's roof. In most of cases, it is made of straight edges with regular angles. In order to define what a regular angle is, a survey has been made on the most frequent values of angles that appear in a reference map. This map contains 2301 angles representing Building wall corners. To compute the percentage of right angles, angles multiple of 45 degrees and angles non multiple of 45 degrees within the dataset, several ranges have been considered. For example, considering a range of 1^o, all angles between 89^o and 91^o are supposed to be 90^o angles. Let us also assume that angles made from small edges (length lower than 2m) are errors coming from the digitization process and make again the same experiments with the remaining angles (1366).

The results of this survey are presented in figure 3.1, table 3.1 and table 3.2. More than 75% of angles are multiple of 45 degrees. If we assume the reference map used to be a good representative and that wall corners have the same characteristics as roofs corners when dealing with 2D building outlines, a regular angle can be defined as an angle whose value is a multiple of 45^o. But a robust algorithm for the determination of building outlines has to take into account angles that are non multiple of 45^o.

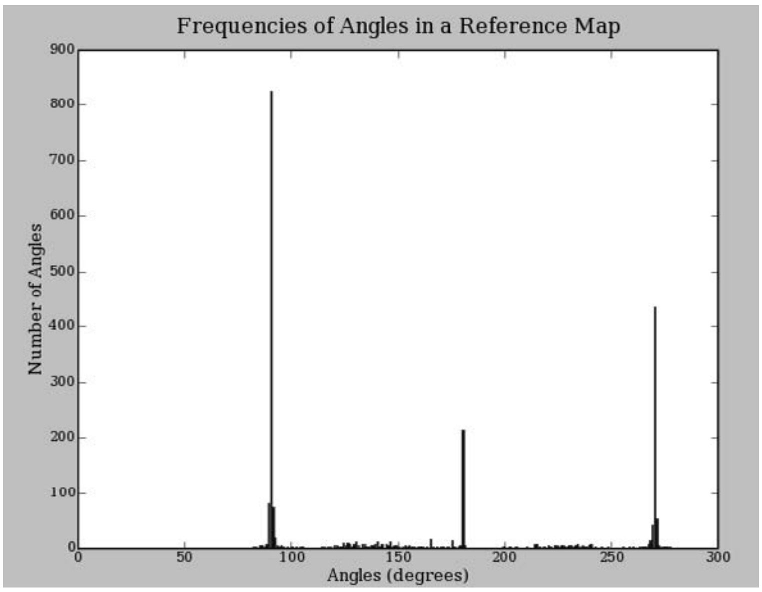


Figure 3-1: Frequencies of angles in a reference data (Interval=1 degree)

Table 3-1: Survey of angles in the reference data (All angles)

Range (degrees)	Right Angles (%)	Angles multiple of 45 degrees (%)	Angles non multiple of 45 degrees (%)
1	73.5	74.6	25.4
2	76.8	78.4	21.6
3	78.0	80.6	19.4
4	78.7	81.9	18.1
5	79.4	83.9	16.1

Table 3-2: Survey of angles in the reference data (Angles whose both edges have a length lower than 1m are excluded)

Range (degrees)	Right Angles (%)	Angles multiple of 45 degrees (%)	Angles non multiple of 45 degrees (%)
1	83.9	85.0	15.0
2	87.9	89.0	11.0
3	88.8	90.4	9.6
4	89.3	91.0	9.0
5	89.8	92.0	8.0

Geometrically speaking, a building outline is a set of 2D coordinates of points arranged in a certain order. Joining successively these points will produce the outline needed.

A good outline has a minimum number of points. Only necessary corners have to be represented. In addition, the outline is correctly determined when the polygon contains all points reflected by the buildings' roofs with the lowest possible surface and perimeter.

The above definition of a 2D building outline as well as the results of the survey will guide the design of the strategy for the determination of a building boundary.

3.2. How to determine 2D building outlines?

The proposed method for the determination of 2D outline of a building is a coarse-to-fine process. The idea is firstly to determine the outer points among the points reflected by the building's roof and then reduce progressively the number of outline points by creating straight edges without damaging the general shape of the outline. Because at least 75% of outlines angles are right, a first attempt of the boundary will be created using only right angles. In case of unsatisfactory results, a second option will be considered where the outline angles are multiple of 45^o. If it happens that the resulted boundary is still unacceptable, in a last approximation, the building angles will not be forced anymore to have pre-defined values. The obtained edges will be displaced towards the exterior of the roof such that the maximum of points fall inside the outline. The methodology divided into several steps as shown by the figure 3.2 is explained in the following sections.

3.3. Pre-processing

In order to extract points reflected by buildings' roofs, a segmentation process is performed. In this work, segmentation stands for the process to detect planar roof faces in laser scanner point clouds. The main assumption is that building roofs are made of planar faces. Once the points reflected by each of the faces are grouped into one segment identified by a number or a colour, it makes easier to recognize and extract building roof points which are the input data for the algorithm to be designed.

3.3.1. Point cloud Segmentation

The segmentation method used in this research described in [Vosselman, 1999] is the plane growing of points based on 3D Hough transform seed selection.

The idea is to detect planar faces by an iterative search, starting with a seed and then growing the latter when a point in the neighbourhood satisfies co-planarity criteria.

To determine the parameters of the seed plane, a modified version of Hough Transform technique [Hough, 1962] is applied. In its original form, it is used to detect 2D objects such as lines in an image. In this case, the underlying principle is to determine the plane equation that fit most closely to selected points. The plane equation is in the form of $d = x\cos(\theta)\cos(\lambda) + y\cos(\theta)\sin(\lambda) + z\sin(\theta)$ where d is the distance from the plane to the origin of the coordinate system (O), θ the angle between the Z-axis and the line joining O to the current point (M) and λ represents the angle between the X-axis and the projection of line (OM) onto the plane (O,X,Y). While applying 3D Hough Transform, instead of working in the object space, bins are defined in the parameter space. This means that some range of discrete values are set for the parameters d, θ, λ, and each time a point satisfies to the equation, the corresponding bin counter is incremented by one. The seed corresponds to the bin with the highest count.

Joining a point to a growing segment is mainly based on distance thresholds. First a threshold is set on the proximity distance meaning the distance between the candidate point to the neighbouring point in the segment. A second threshold is set on the orthogonal distance between the candidate point and the plane defined by points already belonging to the segment.

3.3.2. Identification of buildings

The identification of buildings is done visually and is facilitated by the segmented dataset and the 3D visualization mode.

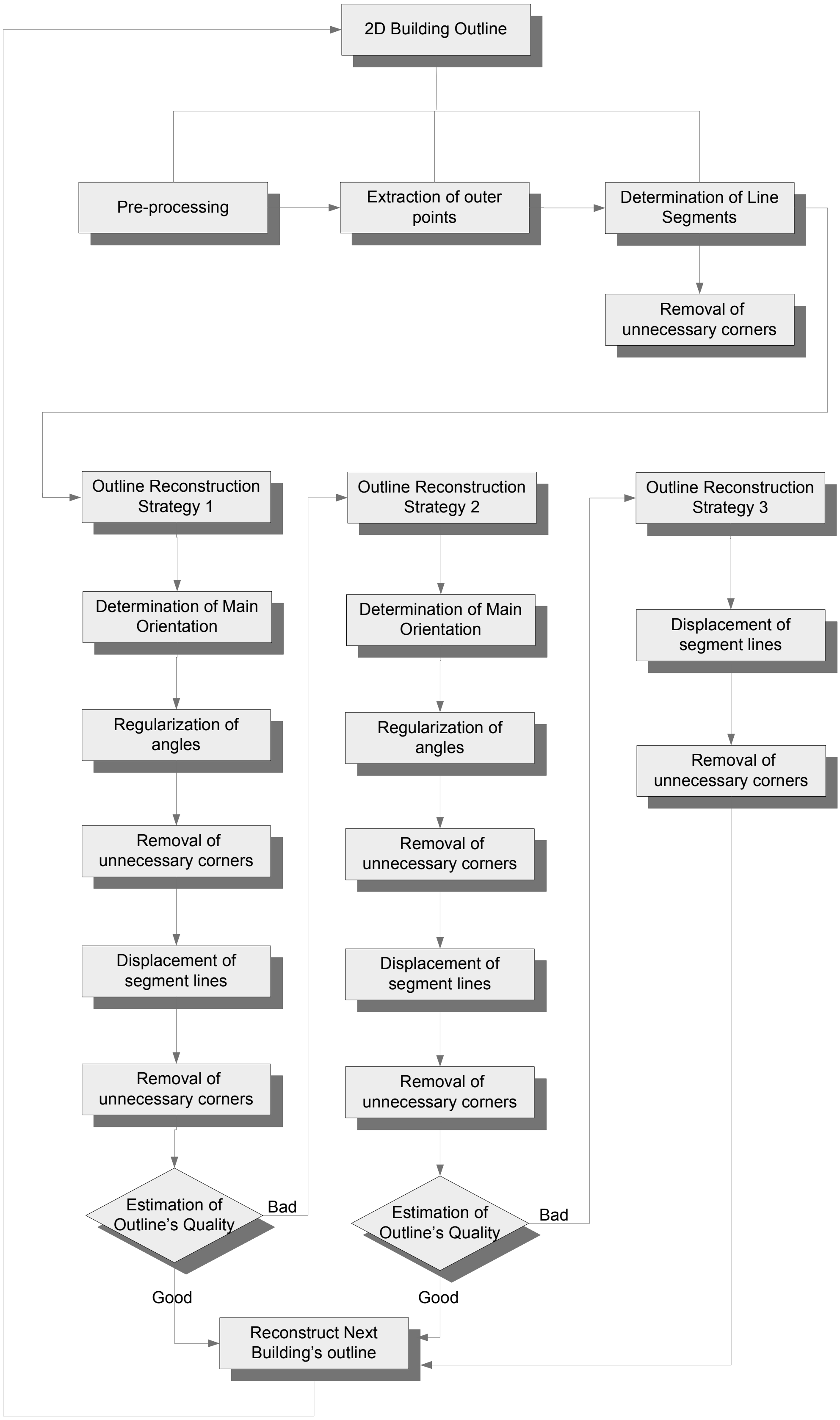


Figure 3-2 : Methodology for determination of 2D outline

Instead of selecting and extracting manually the desired points, some methods exist for the classification of laser points into building and non-building classes. Afterwards, a segmentation process will be carried out where points are grouped per building. But in this research, attention is focused only on the determination of the 2D outline. This is the reason why no filtering or classification program has been designed or implemented in this work.

3.3.3. Selection and Extraction of roof points

During the selection of points, a problem may raise. The roof segments resulting from the segmentation process may not contain only points reflected by roofs but also points in the neighbourhood of the buildings that satisfy the co-planarity conditions. Integrating such points that are not part of the roof can lead to some errors during the determination of building outline. Therefore, after selecting the required segments, available tools within PCM have to be used to remove undesirable points.

Before moving to the following step, the data is cleaned by removing duplicate points. Also, if several points have same horizontal position and different altitudes, only one is kept as the objective is to determine 2D outline.

3.4. Extraction of outer points of the building

This step takes as input all points reflected by building roofs and produces as output the outer points sorted in the clockwise order starting from one of the corners of the dataset. The objective is to generate a first approximation of the outline with the maximum number of corners which contains at least 99% of points reflected by the roofs.

To achieve this goal, the method of a modified version of the convex hull has been adopted. This technique proposed by Jarvis (1977) was used by Sampath and Shan (2007). The convex hull is the smallest convex boundary containing all the points. The use of a modified version of Convex Hull instead of the original version is justified by the fact that the original Convex Hull doesn’t provide a boundary with all necessary corners. Some concave corners are missing in the outline.

The process starts with the determination of one of the corners. The following corners are determined successively. A moving window centred on the current corner is used to collect neighbouring points. The second outline corner is the point that forms with the first corner the least azimuth. For the remaining corners, the exterior topographic angle between the previous corner, the current corner and each of the selected points is computed. The next corner of the outline is chosen in such a way that the computed angle is the least and the current segment line doesn’t cross over any previously determined segment. The principle is made clear by the figure 3.3.

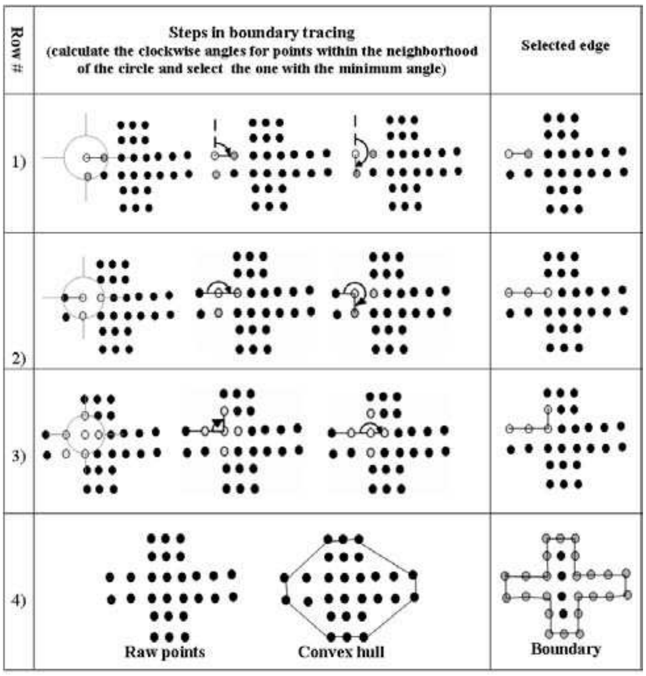


Figure 3-3: Principle of the modified version of Convex Hull

[Sampath and Shan, 2007]

In the modified version of the convex hull formation algorithm, the search window is a rectangular neighborhood centred on the current point. The definition of the size of the search window is critical. Indeed, a too small window will not provide enough points and therefore the determination of outline can be stopped for not finding the following point. A too large search window may contain several corners such that some important corners may be missed in the outline. This is illustrated in the figure 3.4. Empirically, it has been found out that 3 times the point spacing of the dataset is an appropriate size for half the length and the width of the search window. The point spacing can be defined as the average distance between the points of the dataset. To compute the point spacing, the irregular triangulated network (TIN) based on Delaunay triangles is created. The point spacing is taken as the median value of the lengths of all triangle edges. The median value has been chosen because it is the closest value to the majority of the lengths of triangles edges. In order to make this process work for any laser dataset, the size of the search window and consequently the point spacing are computed on the flow and not entered as pre-defined values.

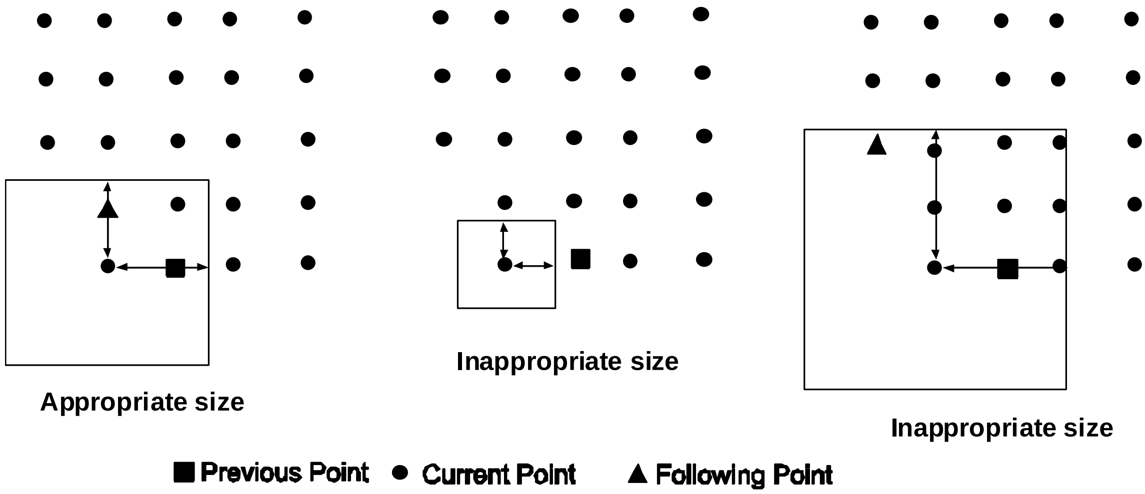


Figure 3-4: Appropriate size for a moving window in the determination of Convex Hull

For a homogeneous dataset, a fixed window size is likely to produce good results. Indeed, it will always be possible to collect enough points and to select the appropriate following point. In case the data is irregularly distributed (clusters of points separated by empty space), the size of the window has to vary locally. In an irregular area, the size of the moving window will be multiplied by two or a higher number. Taking into account the homogeneity of the dataset in the determination of the concave hull was not part of the approach designed by [Sampath and Shan, 2007]. This research has improved the methodology in that direction.

The polygon of outer points can also be obtained by considering the alpha shapes. An α-shape of a finite set of points is a polytope (generalization of 2D polygon to any dimension) that is uniquely determined by a point set and a real number α. α is equal to inverse of a radius of a circle which has on its boundary two points from the point set. The α-shape is neither necessarily convex nor connected. For α=0, α-shape is identical to the convex hull. As α decreases, the α-shape shrinks by gradually developing cavities. More information on this method can be found on [Belair, 2008]. The 2D α-shape has also been implemented in the software Matlab.

3.5. Determination of line segments

As buildings are made of straight edges, the outer points obtained from the previous step are grouped to form line segments. A line segment has only two points and is described by its orientation and its position. Determining line segments means replacing a set of points that fall within some conditions by a regression line segment that fits the best to these points. The orientation of the line segment is computed by a least squares adjustment while its position is determined by the average coordinates of the points.

The selection of points used to compute the line segments is made by an iterative search. Firstly, the first two points are selected and the equation of the line joining those points is computed. If the orthogonal distance of the following point to the line is less than a given threshold and the azimuth of the line segment made by the second and the current point is within a given range, the current point is joined to the list of points and the equation of the new line that best fits the three points is calculated. The equation is updated until the orthogonal distance between a point to the line exceeds the distance threshold or the azimuth of the current segment is out of range. As shown by figure 3.5, the selection of points using distance to line and azimuth provide better results than considering only the distance to line.

The value of the distance threshold has been established by considering the point spacing of the laser scanner data. It is assumed that during the data collection, the laser points do not follow a specific line direction. They are rather distributed randomly at the right or at the left of any given line with a maximum orthogonal distance represented by the point spacing. To be sure to select enough points, the threshold has been set to one and half times the point spacing. Both the point spacing and the threshold have to be computed in this algorithm on the flow. No previously defined value is used.

To determine the range within which the azimuth of segment made by previously selected point and current point is acceptable, first the azimuth of the first two points are computed. For any point selected, the difference between the azimuths of first and last segment should not exceed 22.5°. This choice can be justified by the main assumption that generally, two consecutive building edges form an angle higher than 22.5°.

Figure 3-5: Fitting line segments to outer points with distance to line and azimuth or with only distance to line.

This step takes as input data the outer points produced in the previous step and generates line segments. The main difference with the previous step is an outline better regularized with a noticeable reduction of the number of outline points.

3.6. Removal of unecessary corners

When dealing with building outlines, some situations appear abnormal and have to be corrected. These situations may appear after the previous step or later in the process. The objective is to use prior knowledge on buildings to remove unnecessary corners without affecting the precision of the outline.

In case two segments are crossing each other, the intersection point is computed and inserted in the outline. All other unnecessary points around this intersection point are removed as shown by figure 3.6.

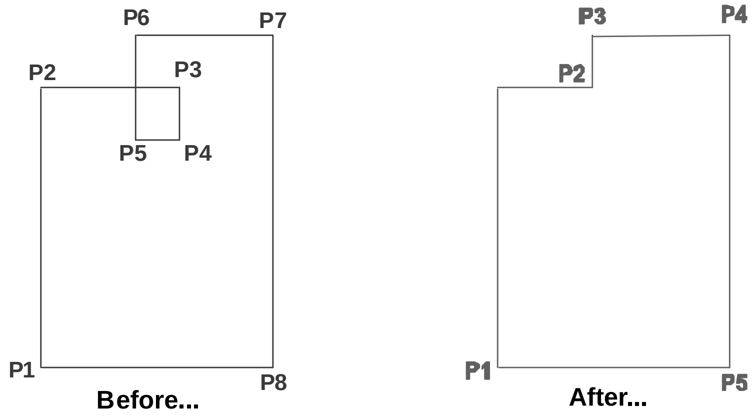


Figure 3-6: Removal of unnecessary corners when two segment lines are crossing each other

When three successive points lie on the same line, the middle one is removed from the outline. Furthermore, if three consecutive vertices form an extremely large angle, the center vertex can be deleted without severely distorting the polygon (Figure 3.7). The condition used to apply this rule is a difference of up to 10^{o} while computing the azimuths of the two segments.

Figure 3-7: Removal of unnecessary corners when points that create with the previous and following point form the same line segment or an extremely large angle

Two successive line segments that are in opposite direction shouldn't occur in a normal outline. To solve this problem, the intermediate point is removed. The difference between two opposite directions is 180^{o}. If this difference is between 170^{o} and 190^{o}, the intermediate point is removed from the list. In the example provided in figure 3-8, initial point P2 is removed.

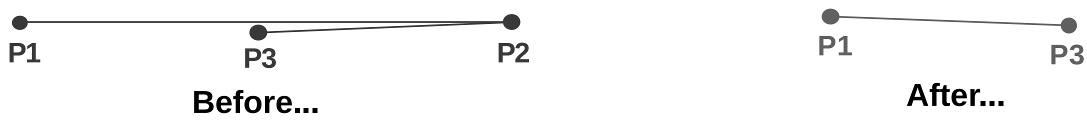


Figure 3-8: Removal of unnecessary corners when two successive line segments are in opposite direction

3.7. Outline reconstruction strategy one

3.7.1. Determination of main orientation

After fitting line segments to outer points and removing unnecessary corners, the main direction of buildings have to be determined before proceeding with the next step which is the regularization of angles. Indeed, the main direction of the building is used to compute the regular angles (See next section). The main direction is computed in two different ways and the one that produces the better outline is considered in the following steps.

The first computation is made by intersecting the most sloped roof face with a horizontal plane and computing the direction of the resulted line. After performing segmentation into planes, segments to which belong the outer points (section 3.4) are extracted. The least squares adjustment technique is used to compute the equation of each of these planes. The slope of each segment is then calculated. The segment with the highest slope is intersected with a horizontal plane. The direction of the obtained line is considered to be the main direction of the building (Figure 3.9). This orientation can also be derived from the outer product of the normal vector of the most sloped roof face and the Zenith axis.

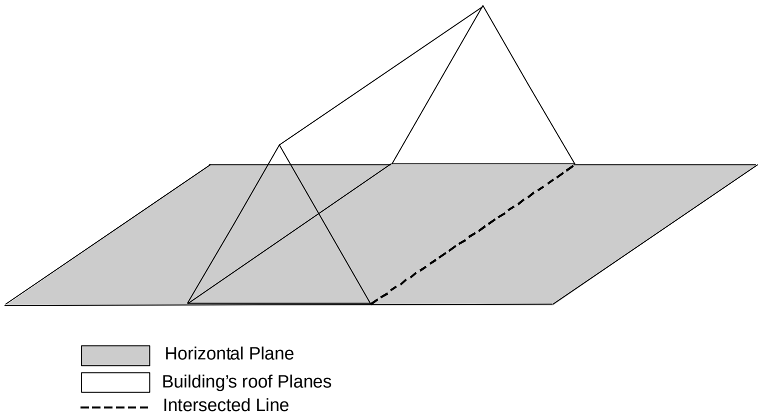


Figure 3-9: Determination of main orientation by intersection

The main orientation of building is also computed by using a second method. After fitting line segments to the outer points and before the removal of the unnecessary points, the main direction of the building is considered to be the azimuth of the longest segment line.

Both of these values are used to reconstruct the outline. The one that provides an outline whose surface is closest to the one of the polygon made by outer points is considered to be the best one.

3.7.2. Regularization of angles

In this section, regularization means the change of angle values into right angles such that the final roof outline has a regular geometric shape. The main direction computed in the previous section as well as the orthogonal projection are used to achieve this objective. Every point is perpendicularly projected onto the two possible directions drawn on the previous point. From the two new positions obtained, the selected one is closest to the initial point, P2" in this case. (Figure 3-10)

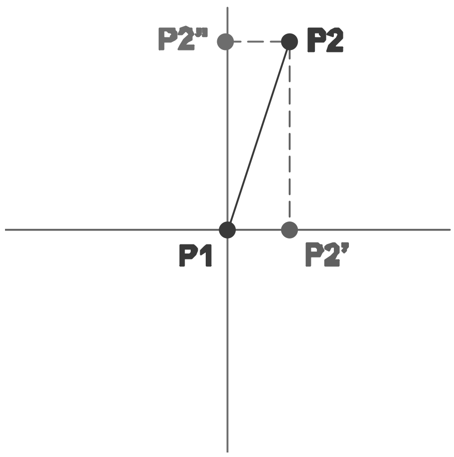


Figure 3-10: Regularization of Angles (Strategy 1)

After making angles regular, unnecessary corners are removed by applying the cases discussed in section 3.6.

3.7.3. Displacement of edges

After making angles right using the principle described in previous section, the following step intends to move the segment lines such that most of the points reflected by the building roof fall within the outline. The objective of the displacement of the segment lines is to determine an outline which contains the maximum number of points. The shifting is made towards the outside of the building. For this purpose, the eventual points lying outside every segment are selected and their distance to the corresponding line is computed. The segment line is shifted parallel to itself to the most outside point, meaning to the point that has the maximum distance. No displacement of an edge is made when there is no point exterior to this edge. Figure 3.11 shows a displacement where the dark edges (original outline) are replaced by the dashed ones.

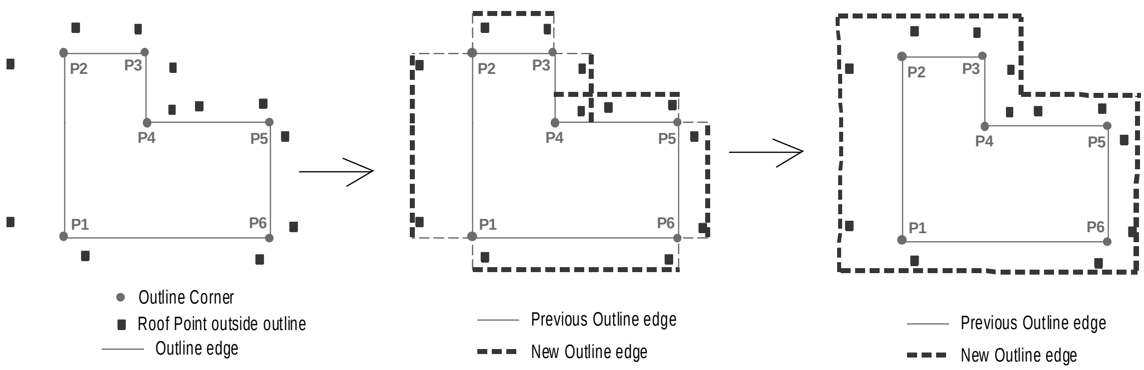


Figure 3-11: Displacement of edges

Once all displacements have been achieved, the intersections of consecutive line segments are computed. These newly obtained points constitute the new outline.

3.7.4. Removal of unecessary corners

After the displacements, again the algorithm of removal of unecessary corners is applied.

The last step of this reconstruction strategy 1 is made of the removal of short segments. If two line segments are separated by a short segment whose distance is lower than a threshold, they are glue together. When gluing two parallel segments, the new position is the most exterior to the roof. In the examples shown on the figure 3.12, the outline points are arranged in clockwise mode and thus the displacement is made towards the left.

The threshold is set to 50 cm because in general, most of building edges are longer than this value.

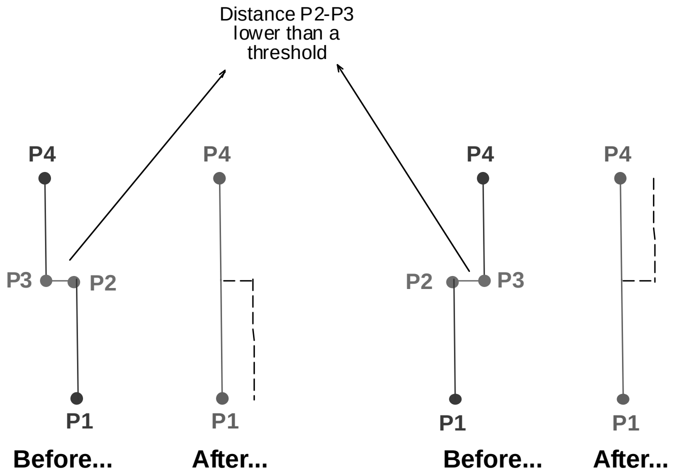


Figure 3-12: Removal of small segments

3.7.5. Estimation of Outline's Quality

At this level, depending on the quality of the computed outline, either the outline is accepted or the process continues with the next reconstruction method. The quality is measured by comparing the outline obtained with the polygon of outer points. Two parameters are computed: the percentage of points inside the determined outline and the difference in surface between the computed outline and the polygon of outer points. As shown by figure 3.13, this difference should be as lower as possible. The idea behind the definition of these two criteria is to fit the outline to the dataset without having roof points outside. Thus, if less than 98% of the points fall inside the outline or the difference in surface exceeds 8% of the surface of the polygon of outer points, a second attempt to draw the outline will be made, considering not only right angles but angles multiple of 45^o. This is the objective of the reconstruction strategy 2.

These two thresholds, (98% and 8%) have been defined empirically by observing the different results obtained.

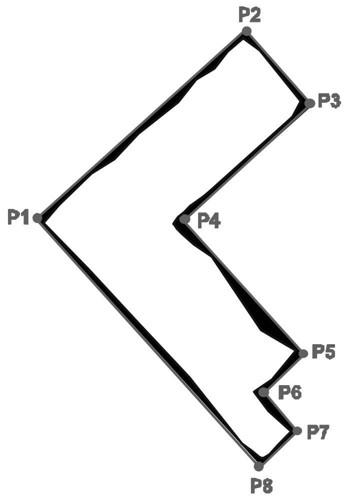


Figure 3-13: Difference in Surface (Black area) between computed outline and Polygon of outer points

3.8. Outline reconstruction strategy two

This step is executed if and only if parallel and perpendicular line segments to the main direction are not sufficient to describe accurately the building outline. The only difference between reconstruction strategies 1 and 2 is during the regularization process where for strategy 2 angles are multiple of 45^o and for strategy 1 angles are supposed to be right.

For the regularization of angles, the same principle as applied for strategy 1 holds. Thus, the task is to compute a new position for every point such that at the end, every angle is a multiple of 45^o. All possible directions that a segment line can take are computed by adding 45^o, 90^o, and 135^o to the azimuth of the main direction. For every possible direction, the new position of a point is computed by perpendicularly projecting the previous position to the new direction. Let's consider the segment line P1-P2 (figure 3.14) and assume that the objective is to compute the new coordinates of P2, the new position of P1 already being determined. P2 is orthogonally projected onto each of the new possible directions. Thus four new possible positions are created. The chosen one is the one that is closest in distance to the previous position of P2. In the case of the figure below, the encircled point is the new position of P2. This process is applied for every corner of the outline.

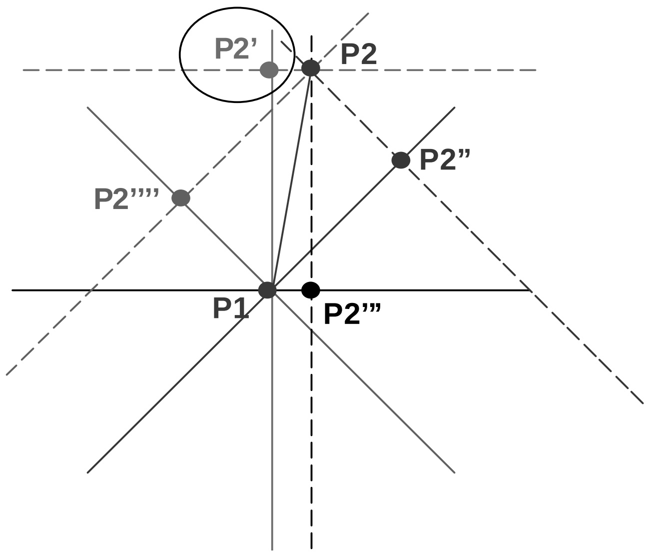


Figure 3-14: Regularization of Angles (Strategy 2)

From the results obtained after the regularization of angles, lines segments are displaced as explained previously. Eventual unnecessary corners are removed. Segment lines whose lengths are lower than 50 cm are discarded. Again, the quality estimator is computed. The two conditions that are required to validate the outline are the same as already stated: 98% of points are inside the outline and the difference in surface with the polygon of outer points does not exceed 8%. In case at least one of these conditions is not satisfied, a final attempt of the outline is made by not forcing angles to take predefined values. The last strategy has been defined for this purpose.

3.9. Outline reconstruction strategy three

This third strategy is carried out by taking the edges obtained after fitting segment lines to outer points (section 3.5) and by making them as straight as possible while removing small ones. In this strategy, no main direction is computed and no regularization of angles is performed.

The process of removal of unnecessary corners as already explained is applied. In addition, the two following situations are executed if needed.

When two successive line segments are likely to be parallel and the distance between them is lower than 50 cm, the intermediate points are removed and only the two extremities are remained (Figure 3.15). Two parallel edges have the same azimuth. The condition used to apply this rule is a difference of up to 10^{o} while computing the azimuths of the two segments.

Figure 3-15: Removal of unnecessary corners when two successive line segments are likely to be parallel and the distance between them is lower than 50cm

For two successive line segments that are not likely to be parallel and the distance between them is lower than 50 cm (Figure 3.16), the intermediate points are removed and replaced by the intersection of the two line segments.

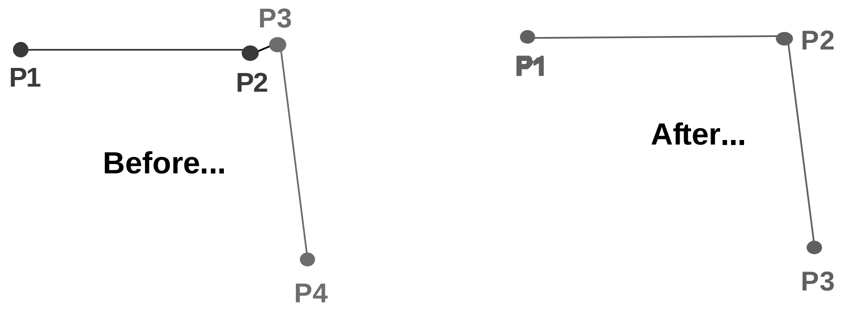


Figure 3-16: Removal of unnecessary corners when two successive line segments are likely to be perpendicular and the distance between them is lower than 50cm.

The process continues with the displacement of segments. Finally, the generalisation is carried out by removing eventual remaining short edges (shorter than 50cm).

3.10. Why is this strategy different from existing approaches?

The strategy developed in this research takes some advantages from existing approaches and also introduces some additional concepts.

Indeed, the outer points are determined based on the method used by [Sampath and Shan, 2007]. But this strategy has been improved by considering situations when the points are irregularly distributed in the dataset. This is achieved by using a locally variable size window.

To replace a series of points likely to be positioned on a same line, a modified version of the least squares adjustment proposed by [Vosselman, 1999] is applied to determine the orientation of the segment lines. The difference appears in the selection of candidate points where not only an orthogonal distance to line is used as criterion, but also a range on the azimuth of edges.

To determine the main direction of the building, it has been considered one aspect that has not been addressed in literature so far which is the outer product of the normal of the most sloped roof plane with the zenith axis.

Another particularity of this algorithm is that if offers three different configurations of the outline and selects the best one based on some criteria.

4. Implementation and Results

This chapter will focus on the implementation of the strategy designed in the previous chapter. Section 1 will describe the study areas and the selection of sample buildings used to test the algorithm. In section 2, the intermediate results corresponding to each step of the strategy and the final ones will be presented. In the last section, the quality of the outlines will be discussed.

4.1. Study areas and input data

On March 14th 2007, Fugro-Inpark B.V. surveys a part of Enschede, Netherlands with FLI-MAP 400 system. Fugro-Inpark B.V. is an independent engineering and consultancy company that offers expertise and project support in the areas of geographic information system technology and their applications, laser altimetry, photogrammetry, subterranean infrastructure, telecommunications, and civil engineering. FLI-MAP 400 system consists of an airborne laser scanner, a digital aerial camera and two video cameras. As illustrated by figure 4.1, the data is collected with a helicopter which contains a laser scanning sensor and some GPS receivers. The flying height was 275 meter above ground.

The datasets produced includes point clouds and orthoimages. The point density depends on whether the objects considered have been recorded in a strip overlapping area or in an area that is covered by a single strip. It also depends on how many returns per pulse were recorded. For the buildings used in this study, the point density varies from 8.5 to 56.6 points per square meter.

To test the proposed algorithm, three different areas have been selected. Figure 4.2 illustrates the survey area as well as the selected study areas.

100 buildings have been selected over the three different areas. In order to measure the robustness of the strategy, the criteria used in the selection of buildings is the variety in shape, size and orientation. Another criteria used for the selection of some buildings is the fact that part of the roof points are missing due to the presence of water.

4.2. Results

In this section, the idea is to present the results of three buildings that have been computed with each of the three reconstruction strategies. Figure 4.3 shows the points reflected by the roofs of these buildings coloured by segment which is the input data for the algorithm. Figure 4.4 presents the results of the first step of the process where the outer points are extracted. The next figure (4.5) shows the line segments that are created to fit the outer points. The angles of the outlines obtained are then regularized; which is followed by the displacement of edges and the removal of unecessary corners. The final results obtained after elimination of short line segments are shown in Figure 4.6.

The results for all buildings are presented in appendix A. First the outlines are superposed to the segmented point clouds. Afterwards, the outlines are superposed with the orthoimages of the same area.

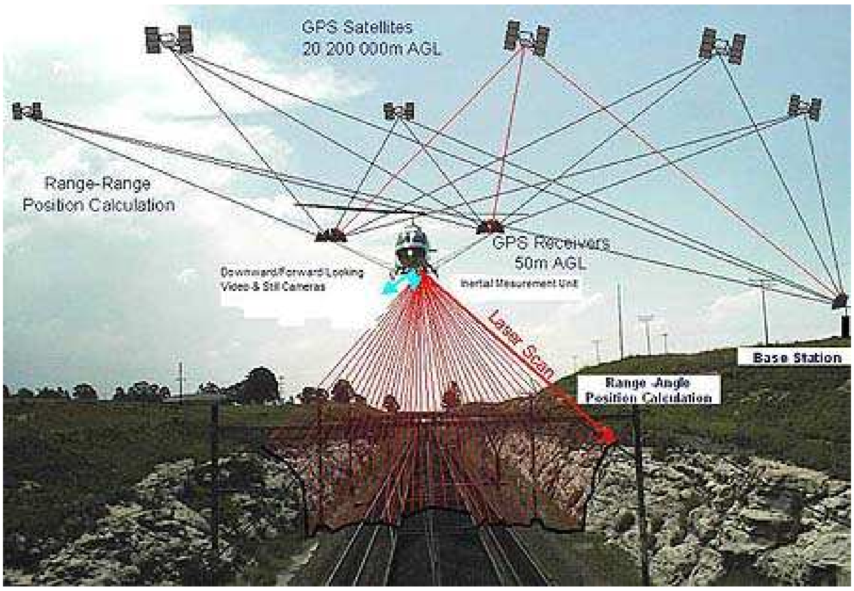


Figure 4-1: FLI-MAP 400 system

[http://www.flimap.com/site4.php] (Accessed December 2007).

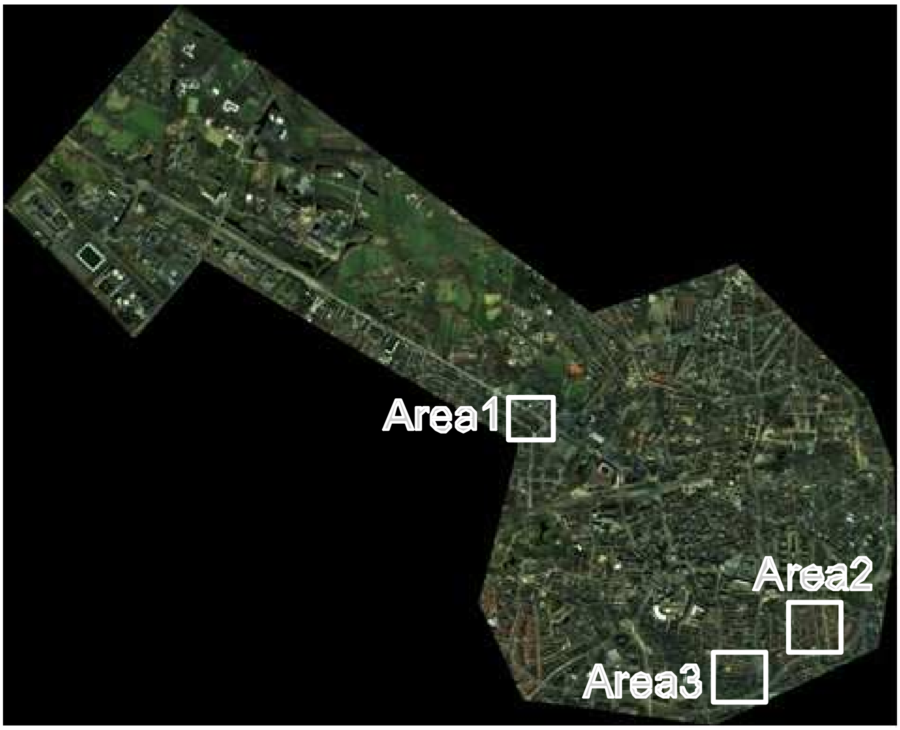


Figure 4-2: Survey area and Study Areas (in red)

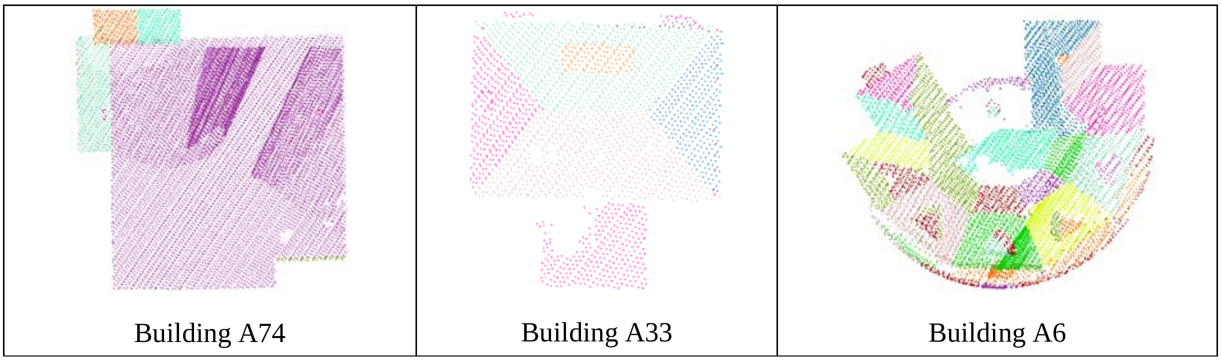


Figure 4-3: Roof points colored by segment

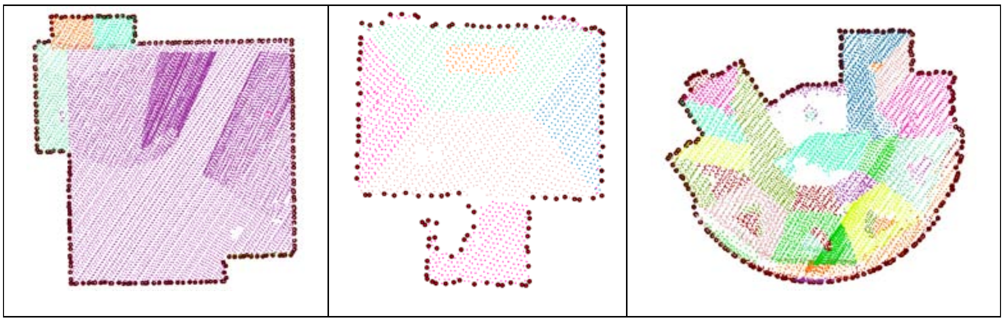


Figure 4-4: Input data and outer Points

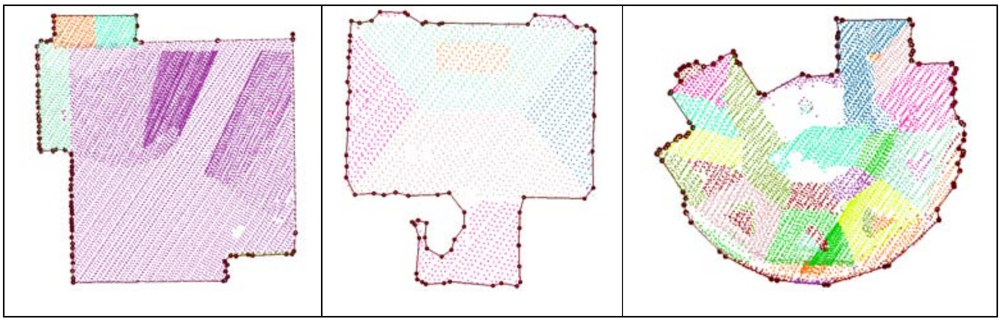


Figure 4-5: Input data and line segments

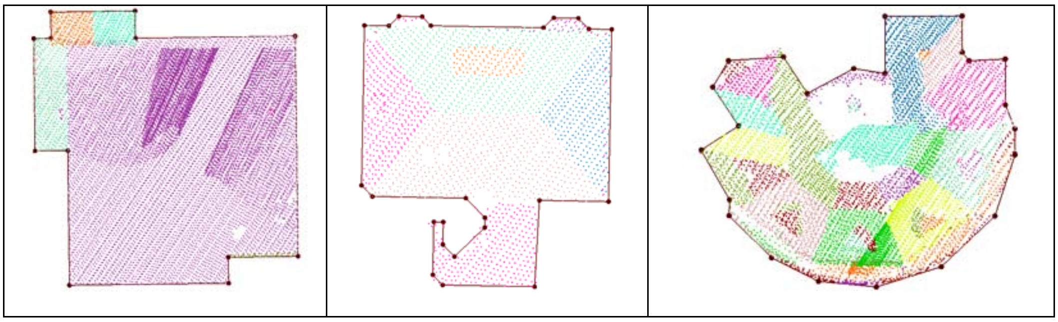


Figure 4-6: Input data and Outlines after angle regularization, displacement and removal of unnecessary corners

4.3. Visual check

88% of outlines have been reconstructed with strategy 1, 3% with strategy 2 and 9% with strategy 3. This first observation is realistic as most of buildings have only right angles (section 3.1).

4.3.1. Superposition with lidar points

At a first glance, it can be noticed that the outlines fit to the lidar points (Appendix A). Most of edges are straight and it has not been noticed neither edges that are crossing each other nor several points that are lying on the same line segment. However, few irrelevant and missing corners have been noticed in some outlines.

4.3.2. Superposition with orthoimages

In general, the outlines reflect the buildings' shape, size and orientation (Appendix A). It can be noticed in some areas a systematic shift between the outlines and the orthoimages. This is probably caused by the inaccurate geo-referencing of the images.

4.3.3. Superposition with building footprints

A digital map containing 2D outlines of the study area has been provided. This map shows the building footprints. In others words, the positions recorded are those of the corners of the walls and not the ones of the roofs. Therefore, this map cannot be used as a ground truth for this study. But as the outlines determined represent the roof outlines, this data should be contained in the determined outlines; which is the case as shown by the figure 4.7. Another observation that can be made from this superposition is the correct orientation of the determined outlines (same as the footprint outlines).

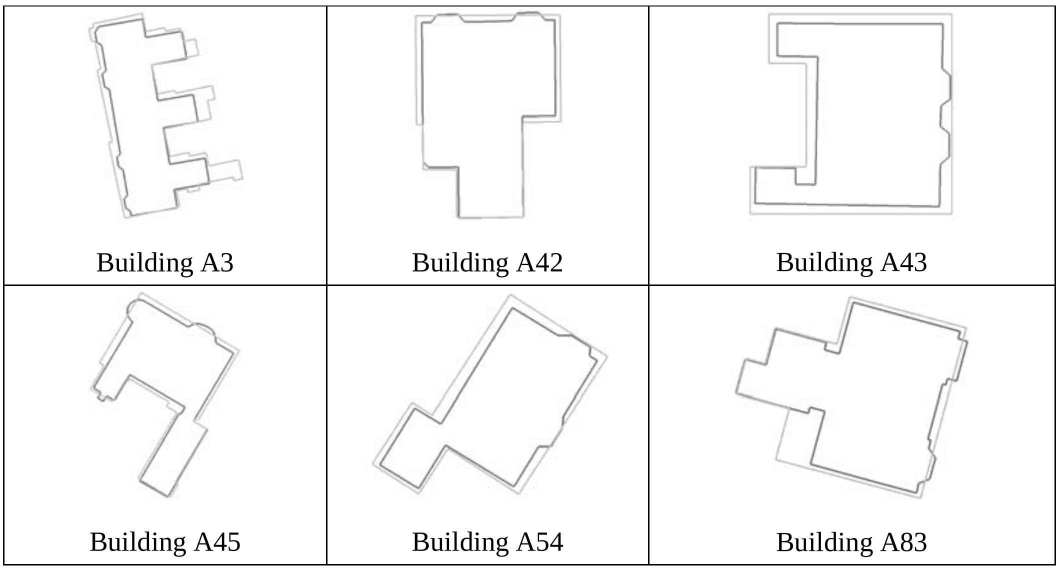


Figure 4-7: Superposition of roof outlines (gray) and footprint outlines (black)

4.3.4. Superposition with reference data

The reference data created manually are compared to the outlines computed manually. Figure 4.8 shows that the two sets of polygons are matching with each other even if there are some minor differences.

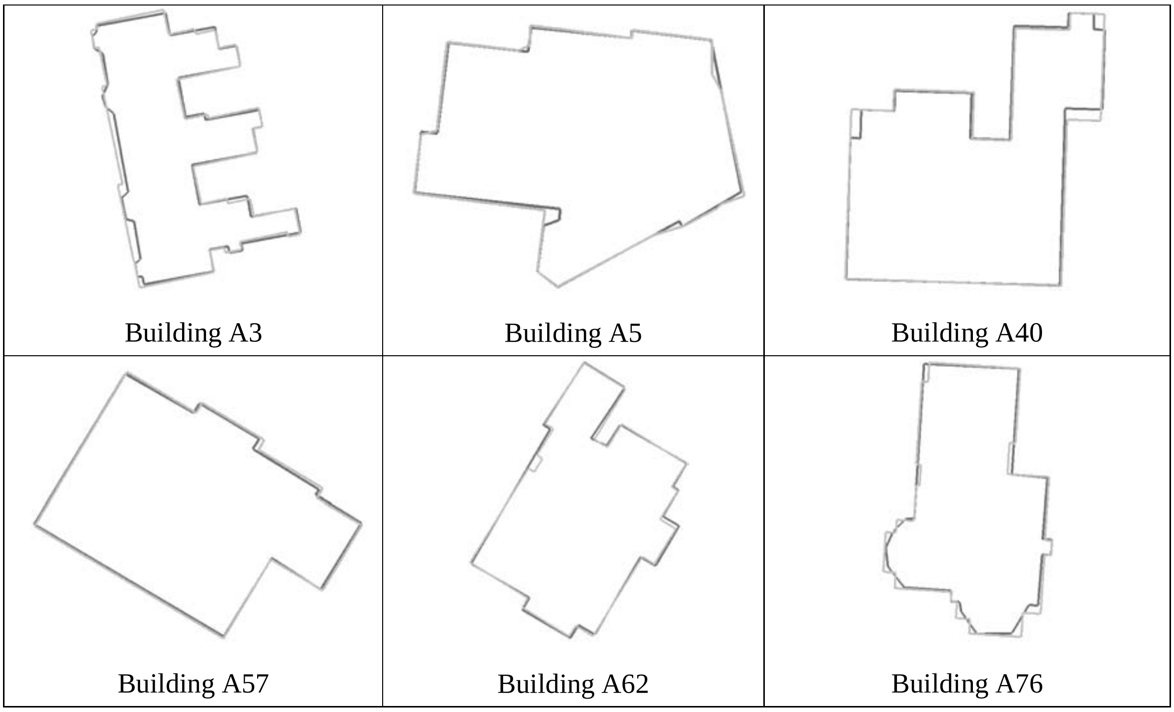


Figure 4-8: Reference outlines computed manually (black) and computed outlines (gray)

4.3.5. Comparison with the method implemented in PCM

The outlines of the 100 sample buildings have also been computed using the software Point Cloud Mapper. The method implemented in this software is made of four steps as follows:

1. Segmentation of the point clouds;
2. Determination of dominant directions by intersecting adjacent planar segments, by taking the outer product of the normal vector to the surface and the zenith axis or in case of flat roofs by using the 2D Hough transform;
3. Approximation of contour pieces by straight lines with dominant directions;
4. Closing of gaps between contour pieces. Depending on the size of the gaps and the angles made by neighboring pieces, gaps are filled by intersecting edges, gluing edges or by connecting end points.

A comparison of both sets of results is achieved by computing a four-grade classification (Appendix B), which is summarized in table 4-1. The four classes defined are:

1. Correct general shape with required number of corners
2. Correct general shape with fewer or higher number of corners

3. Incorrect shape
4. Failed to be computed

From the results of this classification, it can be concluded that the designed approach provides better results as for every class, the percentage of good results obtained for the designed approach is better. But the current algorithm is slow. This is mainly due to the implementation into the interpreted version of Python which reads the program and runs it line by line. The same approach implemented with the programming language C++ using a compiler instead of an interpreter will be much quicker. Also, by creating a kd-tree, access to points will be quicker.

Table 4-1: Comparison of method implemented in Point Cloud Mapper and Current Approach

	Correct general shape with required number of corners (%)	Correct general shape with fewer or higher number of corners (%)	Incorrect shape (%)	Failed to be computed (%)
Approach implemented in Point Cloud Mapper	27	55	16	2
Current Approach	57	43	0	0

4.3.6. Conclusion of the visual check

From these general observations made during the visual check which are valid not only for outlines with right angles but also for buildings that don't have regular geometric shape, it can be concluded that the outlines appear as faithful boundaries of building roofs even for complex buildings (A5, A6…). In the next chapter, a deeper evaluation of the outlines' quality will be achieved.

5. Accuracy Assessment

The objective of this chapter is to discuss how accurate are the outlines computed and to emphasize on the algorithm's limitations. In the first step, a quantitative analysis will be completed where the difference between the reference and the obtained outlines will be measured using different parameters. The second section will highlight other limitations of the algorithm. In the third step, the robustness of the algorithm with respect to the point density will be measured.

5.1. Quantitative Analysis

The use of several parameters in this analysis can be justified by the need to bring to light most of the weak points of the algorithm and find the causes in order to improve the algorithm. Appendix C shows the results of all estimated parameters. The numbering of buildings is the same as in Appendix A.

5.1.1. Percentage of points inside outline

As the points are reflected by the roofs, they should be contained in the outline. Therefore, the higher this percentage of points inside the computed outline, the better is the outline. The percentage of points inside the outlines varies from 96.86 to 99.90. The interpretation is that all outlines contain the majority of roof points. However, it is expected that 100% of points must fall within the outlines for all buildings. Hence, the process of displacement should be improved to achieve this result.

5.1.2. Difference in number of corners

More corners than required indicate the delineation of non significant extrusions and/or intrusions. In case, the number of corners is less than expected, the outline has been more generalised than it should. Thus, some parts of the outline have not been delineated.

Only 36% of outlines have the same number of corners as the reference outlines. 34% have fewer corners than required and 30% have more corners than required (Figure 5-1). Some examples are provided in Figure 5-2. In case of building A8, it has been reconstructed by the strategy 1 which considers only right angles. Thus, the idea being to fit as closely as possible to the lidar points, some additional corners were created. The same explanation holds for building A76. For building A29 where some corners are missing, the removal of short edges is the main reason. The polygon of outer points for building A85 doesn't present enough evidence for the automatic detection of the missing corners.

In order to solve most of the cases, the solution proposed is to first generalise the outline by removing some corners and then use the difference between the computed outline and the polygon of outer points to delineate the intrusions and extrusions missing. However, a higher or lower number of corners doesn't mean systematically a wrong result as shown by the examples on figure 5-2. Indeed, the general shape of outlines is still reflecting the contour of buildings.

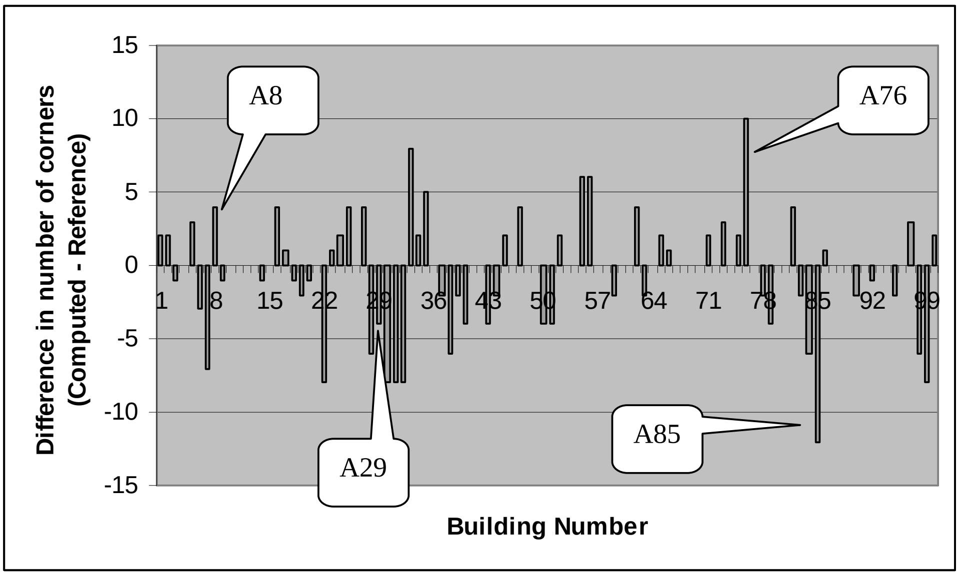


Figure 5-1: Histogram of difference in number of corners

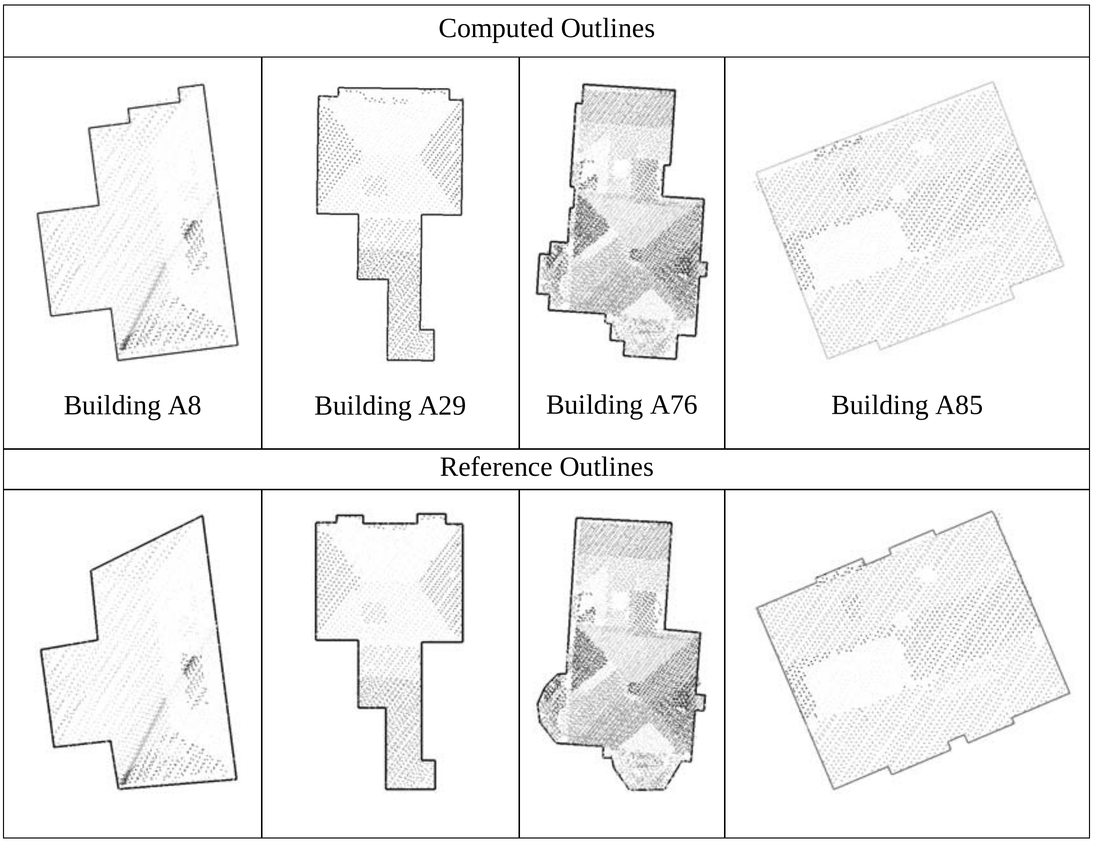


Figure 5-2: Outlines with higher or lower number of corners than required

5.1.3. Difference in main orientation

Determining the main direction is a crucial step in the determination of outlines. Indeed, a wrong main orientation in most of the cases leads to an incorrect outline. Thus, the lower the difference, the better is the outline. The main direction is taken from the longest side of the outlines. Knowing that there is no main orientation for outlines determined with strategy 3 and therefore by considering only results from strategy 1 and strategy 2, for 96% of the buildings, the absolute value of the difference of the main orientation is less than 2^o, which means that most of buildings have been correctly oriented. Critical cases with highest difference in main orientation are discussed using figures 5-3 and 5-4. As building A16 has been reconstructed by strategy 1, the bottom edge has not been properly delineated. The main orientation is taken from this side as it is the longest. By designing a robust strategy that will consider right and non-right angles in the same outline, this problem will be solved. As can be seen on figure 5-4, the difference in orientation for building A73 is acceptable. In conclusion, the process for the determination of main orientation is correct.

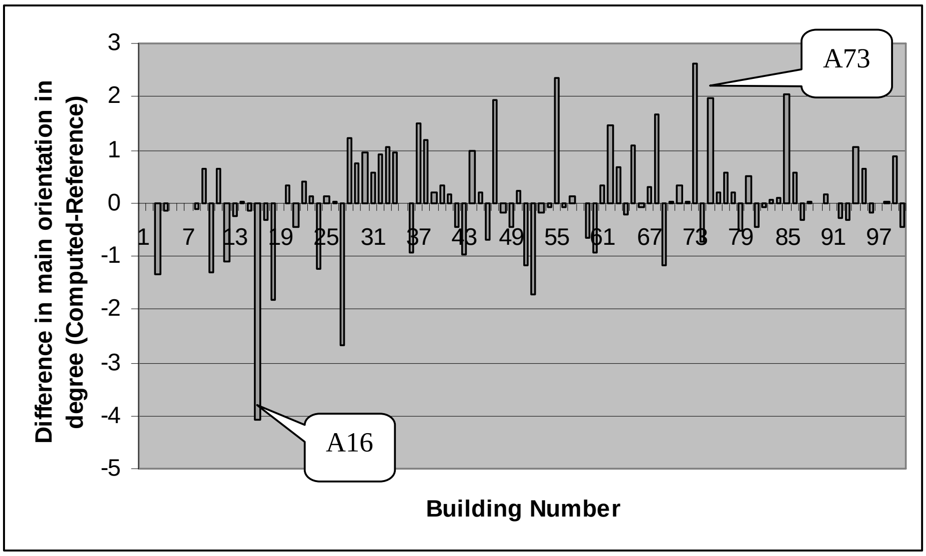


Figure 5-3: Histogram of difference in main orientation

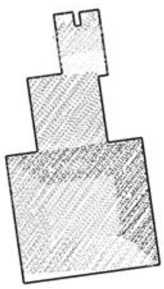
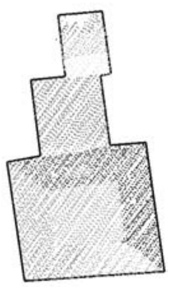
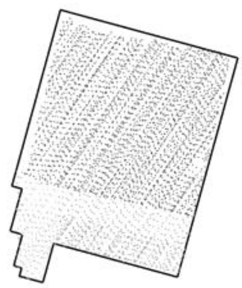
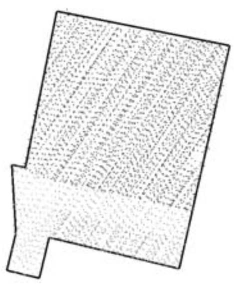
Computed Outline	Reference Outline	Computed Outline	Reference Outline
 Building A16	 Building A16	 Building A73	 Building A73

Figure 5-4: Outlines with highest difference of main direction

5.1.4. Extra difference area and missing difference area

These parameters indicate in relative value the surface where there is no correspondence between both representations. The first indicator represents the percentage of the surface of the computed outline which doesn't match with the reference outline. This value is called extra difference area as it represents an area that should not been delineated. The second indicator is the percentage of the surface of the reference outline that doesn't match with the computed outline. The latter is called missing difference area and it is indicating part of the roofs that have not been covered by the computed outline. Figure 5.5 shows an example of these indicators. The lower these values, the better are the computed outlines.

To compute these differences, the intersection points between reference and computed outlines are determined. These intersection points added to the points of both outlines are used to create a triangulated irregular network. Triangles whose centre of gravity belongs to computed outline but not to the reference outline are used to compute the extra difference area. On the other hand, the sum of the surfaces of triangles whose centre of gravity belong to the reference map but not to the computed outline determines the missing difference area.

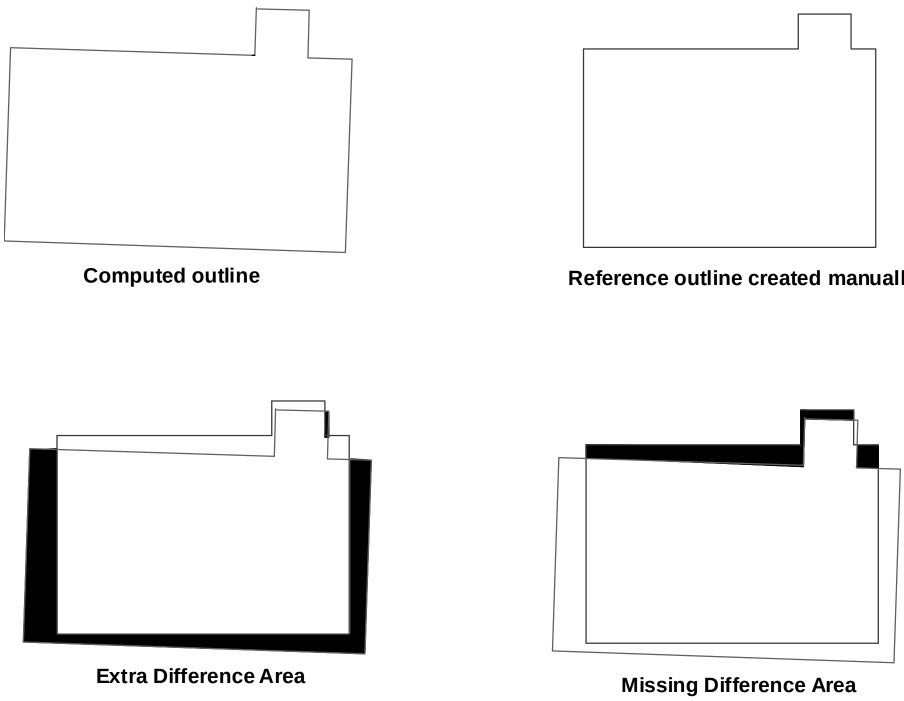


Figure 5-5: Extra difference area and missing difference area

12% of outlines have an extra difference area higher than 4% of their surface; which means that part of the area outlined should not be. Thus, some computed outlines are slightly bigger than they should. Having a look at the most extreme cases (Figures 5-6 and 5-8), the high value of building A67, results from its long edges. Thus a small distance between computed and reference outlines creates a high value in surface. The problem of building A73 is the fact it has been reconstructed with strategy 1 and thus with using two perpendicular directions. This building should have been reconstructed by a strategy that considers various directions with right and non-right angles.

95% of outlines have a missing difference area lower than 2% of the surface of the reference outline (Figure 5-6). The interpretation of this result is that most of the computed outlines cover the maximum area of the roofs. From the figures 5-7 and 5-8, it can be inferred that outlines with high missing difference (A33 and A47) refer to buildings where part of the roof points are missing.

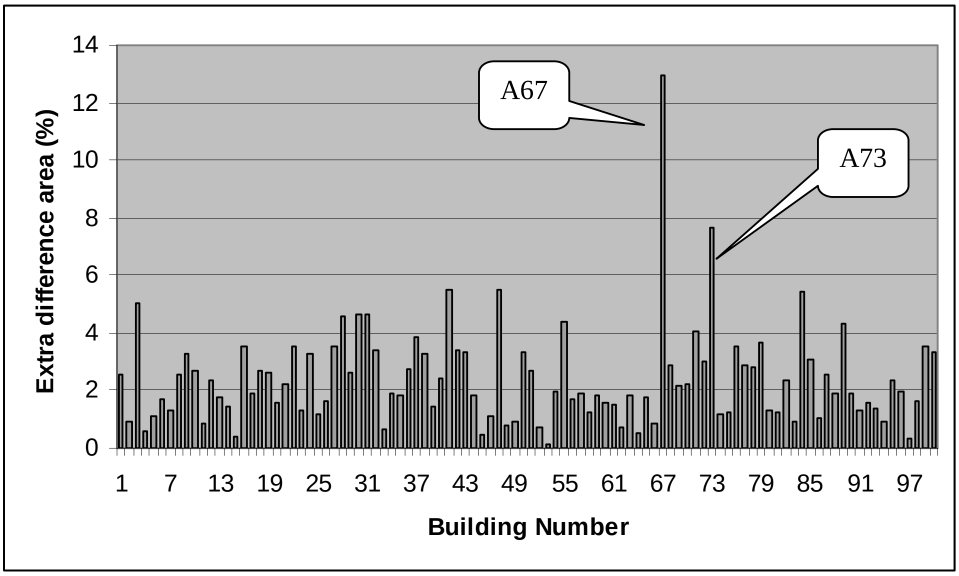


Figure 5-6: Histogram of extra difference area

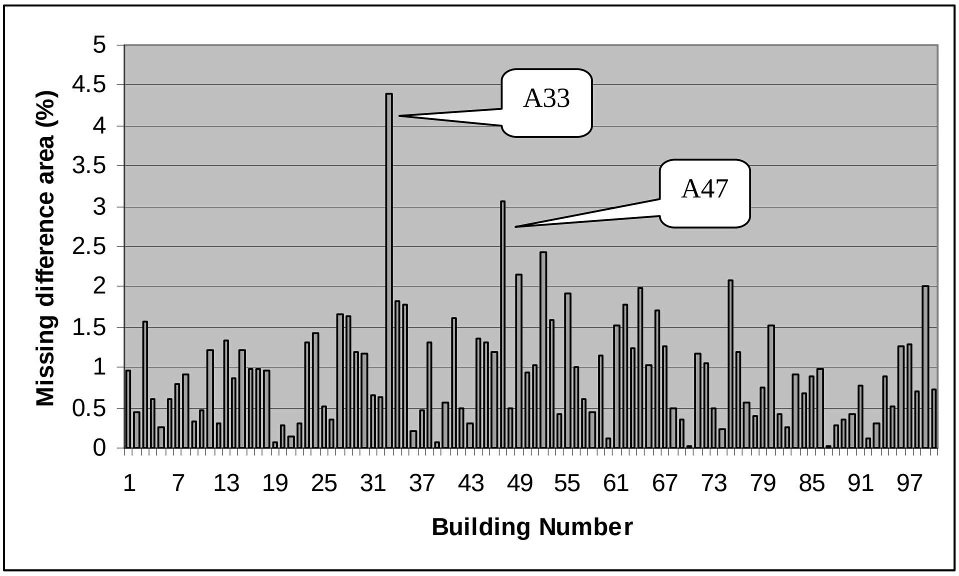


Figure 5-7: Histogram of missing difference area

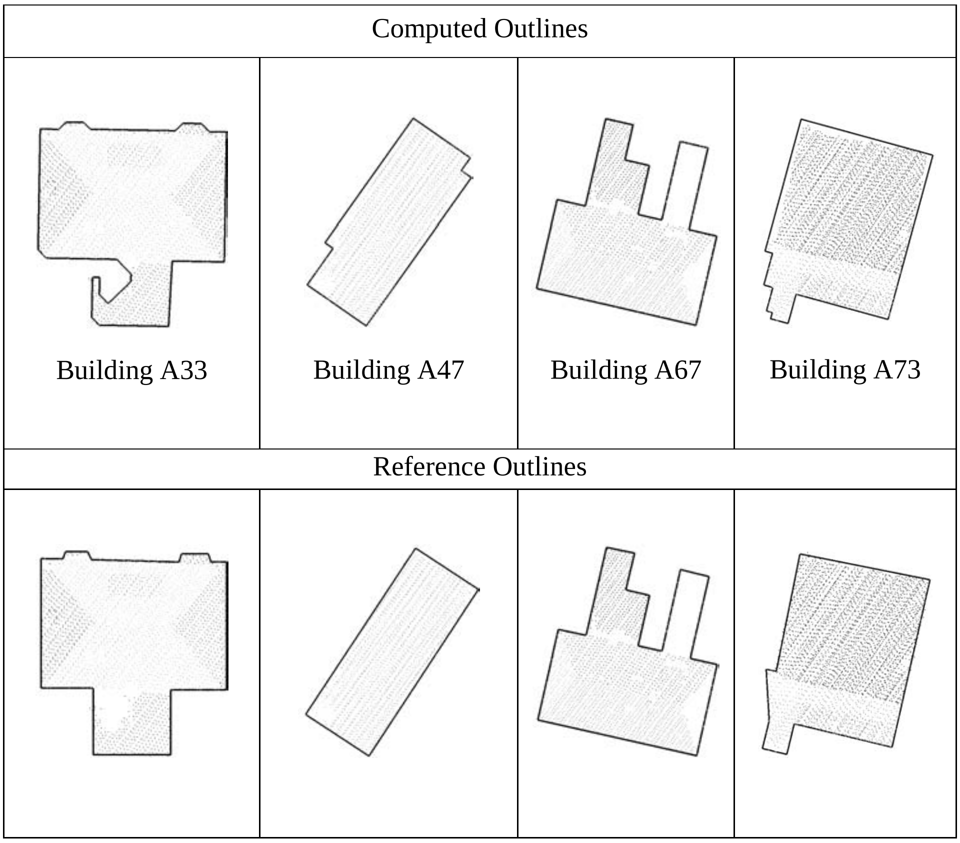


Figure 5-8: Outlines with highest extra and missing difference area

5.1.5. Average distance between reference outline and computed outline

This distance is computed by dividing the symmetric difference area (Sum of extra difference area and missing difference area) by the perimeter of the reference outline. The symmetric difference area representing the total error in surface is thus linearly distributed along the perimeter of the outline.

96% of the average distances are less than 20cm. Only for 4% of buildings that the average distance is up to 35cm.

5.1.6. Conclusion of quantitative analysis

The computed outlines cover the maximum part of the roofs and the average distances between computed and reference outlines are low. In the discussion above, the critical cases have been analysed and it has been noticed that even for these cases, the general shape of outlines still reflect the buildings' boundaries. From this analysis, it can be concluded that the methodology designed to create the 2D outlines gives acceptable results. But the algorithm is not robust enough because the number of corners is not always the appropriate one. The general shape of outlines is correct but the delineation of small details requires additional work.

5.2. Others Limitations of the Algorithm

5.2.1. Limitations of the strategy 3

In addition to generating more or less corners than required, another problem of strategy 3 is about regularization of some angles. This strategy has been designed for building with non regular angles. However, it happens that some of these angles should be multiple of 45^{o}. Thus buildings whose outlines have a mixture of regular angles and non regular angles are not correctly delineated (Figure 5-9 Buildings A7 and A97). The algorithm doesn't take this consideration into account. This situation can be solved by considering the results of each of the three strategies, by taking the best part from each of them and by assembling them. But how to automatically detect the best parts remains the problem to be solved.

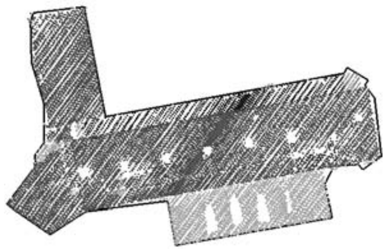
 Building A7	 Building A97

Figure 5-9: Some incorrect outlines

5.2.2. Influence of thresholds

The first threshold is used in the determination of the outer points. It is the size of the search window. It is calculated as three times the point spacing. It can be noticed on figure 5.10 that by tuning this parameter, the number of outline corners is not always the same. Indeed, by changing the size of the search window, the number of outer points collected varies and consequently, the outline computed changes. The final result is slightly sensitive to a variation of this threshold but it still reflects the shape of the building.

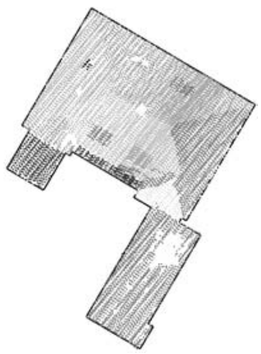
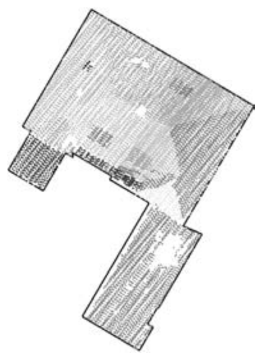
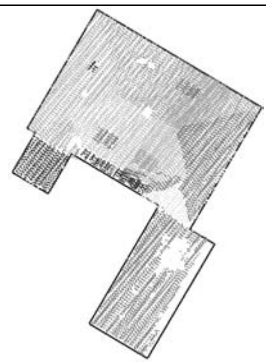
		
Point Spacing =20cm Multiplication factor = 3 (Original values computed automatically)	Point Spacing set as 20cm Multiplication factor = 1.5	Point Spacing set as 40cm Multiplication factor = 3

Figure 5-10: Influence of search window size on the final result (Building A45)

The second and third thresholds (orthogonal distance to a line and minimum angle between two consecutive line segments) are used in the second step of the algorithm where line segments are fitted to the outer points. A small variation of these values doesn't affect significantly the final results (Figure 5.11) but again, it changes the number of corners. Indeed, by varying these thresholds, the segment lines computed to fit to outer points are not the same and consequently the edges obtained after regularization are different.

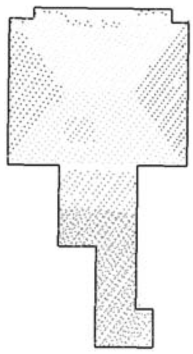
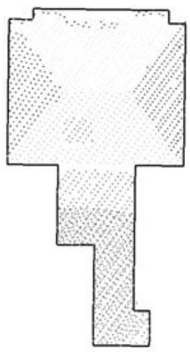
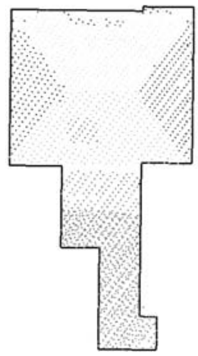
		
Distance Parameter= 1.5 X Point Spacing Angle threshold = 22.5^o (Original values computed automatically)	Distance Parameter= 3 X Point Spacing Angle threshold = 22.5^o	Distance Parameter= 3 X Point Spacing Angle threshold = 45^o

Figure 5-11: Influence of distance parameter and angle parameter on the final result (Building A29)

Other thresholds used in the algorithm are the values considered to estimate automatically the quality of the computed outlines. 98% and 8% are respectively considered as the minimum allowed percentage of points inside the outline and the maximum allowed percentage of difference in surface between the computed outline and the polygon of outer points. These thresholds are used to select the appropriate strategy. Selecting the appropriate strategy is the same as obtaining the best possible outline with the designed approach. By varying these parameters, the number of outlines reconstructed by strategies 1, 2 or 3 varies. It has been noticed that whatever are the values set for these parameters; they do not select for 100% of buildings the appropriate outline strategy. Therefore, the possibility has been offered to the user to select a given strategy or to let the algorithm make the selection automatically. Some simulations have been performed in order to find out the optimum values used for these thresholds (Table 5-1).

Table 5-1: Simulations for determining the optimum thresholds for automatic selection of appropriate strategy

Minimum allowed percentage of points inside the outline (%)	Maximum allowed percentage of difference in surface (%)	Percentage of automatic selection of appropriate strategy (%)
98	8	86

98	10	86
98.5	8	85
98.5	10	85
99	8	83
99	10	82

The last threshold considered is the value of 50 cm representing the minimum length of edges. Again, this parameter has an influence on the final outlines. In some cases, edges with length lower than 50 cm are necessary to properly delineate building outlines.

5.2.3. Problem of Missing data

In the example on Figure 5.12, the lower left of the input data is missing. The reason is the presence of water on top of the roof which causes the laser beam to be absorbed instead of being reflected. The algorithm didn't manage to recognize this gap in the data and draw the outline accordingly. The same algorithm which has to fit closely the lidar points in general, has to outline the empty space in case of missing data. These two tasks are contradictory and more building knowledge is required to automatically recognize and correct for missing data. To solve this problem, once the outline is computed, a systematic search of empty and adjacent neighborhood areas will be performed. Close by areas with a surface higher than a threshold determined based on the dataset point spacing, where no ground point or no tree point is found is supposed to be part of the building. The main assumption that supports this assertion is that in general, no swimming pool or water area is adjacent to building. It is also assumed that the gap in the data is not due to the remote sensor. The outline can then be adjusted by integrating these areas. This suggestion has not been implemented in this work.

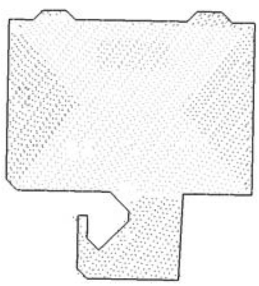
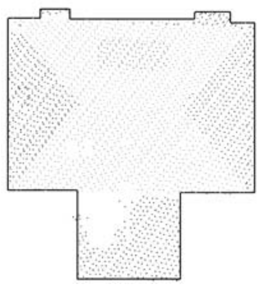
	
Computed outline	Reference outline

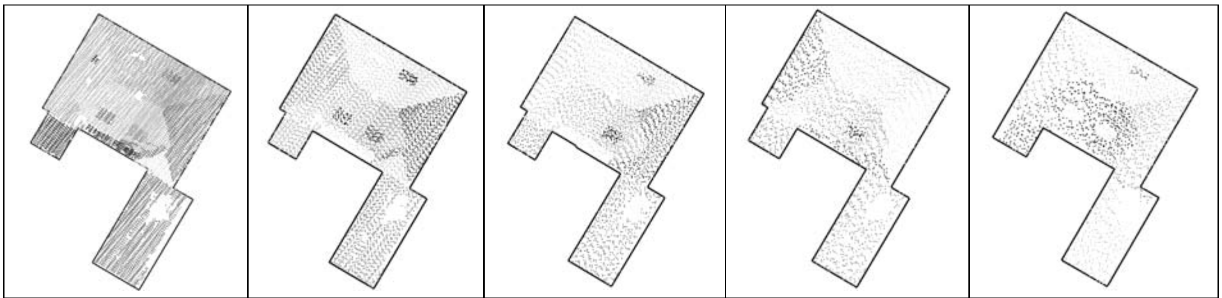
Figure 5-12: Problem of Missing data (Building A33)

Another type of missing data occurs when trees are adjacent to buildings (Building A47). In this case, the segments representing the roof planes are not complete because the presence of trees does not enable this part of the roof to reflect the laser beam. Manual editing is the solution proposed to correct for this error.

5.3. Robustness of the Algorithm in terms of Point Density

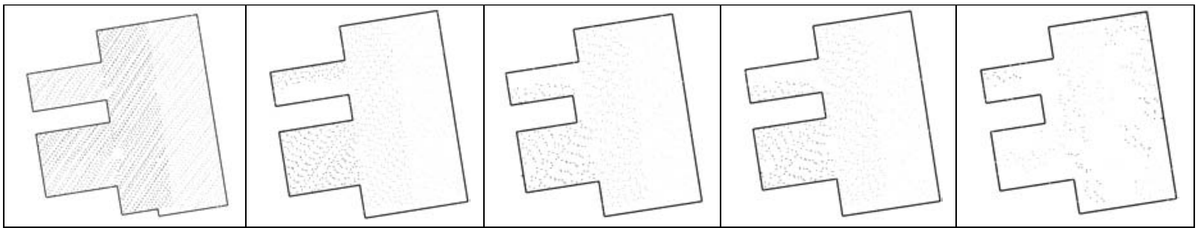
In this section, the idea is to figure out whether a high point density is required to get a correct outline. The experience below is made using the same thresholds. To vary the point density, every nth point of the dataset is kept depending on the reduction rate (n) specified by the user.

PD=Point Density (Number of points per square meter)



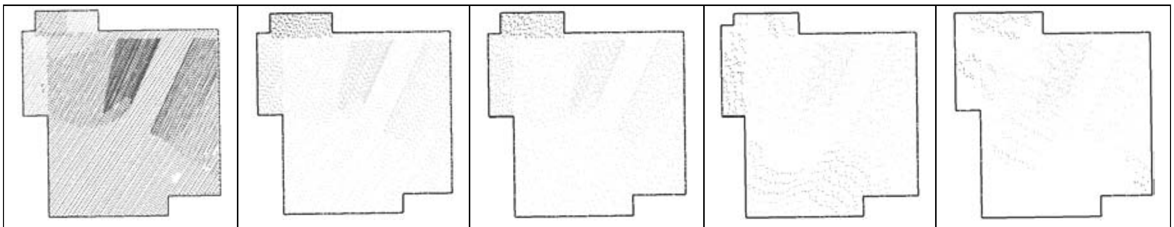
PD= 35.5	PD = 17.8	PD = 12.0	PD = 9.0	PD = 7.2

Figure 5-13: Outlines with various point densities (Building A45)



PD = 15.8	PD = 8.0	PD = 5.4	PD = 4.1	PD = 3.3

Figure 5-14: Outlines with various point densities (Building A24)



PD = 23.1	PD = 11.6	PD = 7.8	PD = 4.7	PD = 3.4

Figure 5-15: Outlines with various point densities (Building A74)

From the figures 5-13, 5-14 and 5-15, it can be concluded that even with low point density, the strategy used provides outlines that correctly reflect the shape of buildings.

6. Conclusion and Recommendations

6.1. Conclusion

Three research questions were supposed to be answered in this study.

The first one is: What are the different methods proposed in literature to extract 2D building outlines using airborne laser scanner data? Among the papers dealing with this topic, thirteen have been chosen and the methodology used has been described and appreciated.

The second research question involves the design of another approach that will automatically reconstruct 2D building outlines based on lidar points. The proposed approach is made of several tasks: Segmentation of lidar points, extraction of roof points, determination of outer points, determination of the main direction of building, regularization of angles and implementation of three reconstruction strategies corresponding to different types of buildings.

The analysis of the designed approach was the objective of the third research question. It has been performed by considering many aspects: superposition with lidar points, orthoimages, building footprints and reference data created manually on one side. On the other side, quantitative analysis, influence of thresholds, robustness, limitations of algorithm and comparison with an existing method were carried out.

Most of outlines reconstructed are correct representations of the buildings' roof boundaries even if the analysis of the approach has shown its limitations. These outlines can be used on maps at a scale of 1:2000 or lower. Indeed the precision of map features can be estimated as 0.1 mm x Scale factor which is equal to 20 cm for 1:2000 maps. 96% of the average distances between computed and reference outlines are less than 20cm; which justifies that the outlines are correct enough for 1:2000 maps. But, depending on the applications and the scale considered, all the details of the outlines may not be needed. In these circumstances, generalization techniques can be applied to reduce the complexity of the outlines. Different building generalization techniques have been developed. The Douglas-Peucker-algorithm has been adapted for building polygons, which is described in [Kanani, 2000]. The Environmental Systems Research Institute (ESRI) designs a tool for simplifying building outlines in ARCGIS. Sester (2000) presents a building generalization method that uses the least squares adjustment.

In case the objective is to use the outlines for a higher scale maps or to reconstruct 3D building models with the correct delineation of small features, some improvement is required. Indeed, it appears that in several cases, the number of corners is higher or lower than expected which means that small intrusions and extrusions are not always properly delineated. In addition, the algorithm is data-driven and couldn't manage to detect some missing data and draw outlines consequently. Furthermore, the results obtained are sensible to the tuning of the thresholds and the automatically computed thresholds are not necessarily the optimum ones. Hence, further effort is required to enhance the methodology.

6.2. Recommendations

For further improvement of the designed methodology, it can be recommended the following:

- Delineate the intrusions and extrusions missing by comparing the obtained outlines with the polygons of outer points obtained using the modified version of the convex hull and by using the extra difference surfaces and the missing difference surfaces as described earlier in this work. The code written for this purpose detects the empty spaces between the polygons and tries to locally improve the computed outline. It solves the problem in some cases (Figure 6-1), but introduces additional noise in others. This idea requires a deeper analysis.

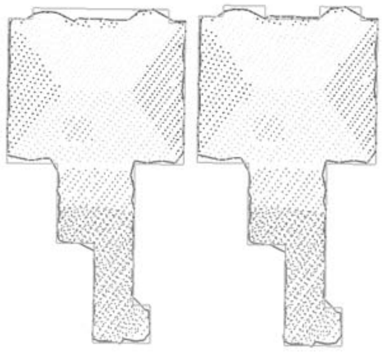


Figure 6-1: Computed outline (Gray) and polygon of outer points (Black)

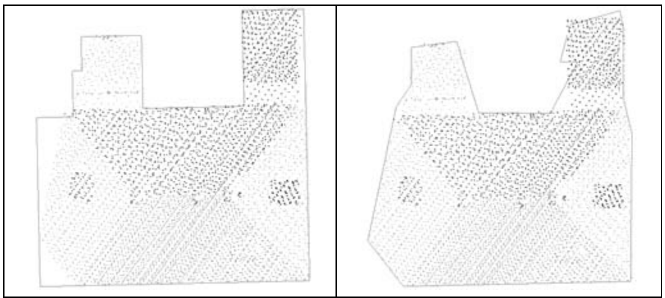
Left: Results obtained - Right: Improved results

-Group strategy 1, 2 and 3 as another alternative apart from strategy 1, by computing each of them and taking the best part from each one. This proposition will solve several limitations of the algorithm: outlines containing more or less corners than needed, outlines computed with strategy 3 that should have some of the angles multiple of 45 degrees if needed. Another reason that justifies this grouping is the limited number of buildings delineated by strategies 2 and 3. For example, to have a correct representation of Building A35, the left side of the main roof can be taken from the outline reconstructed with strategy 3 (Figure 6-2) while the remaining part can be extracted from strategy 1 outline.

To achieve this objective, the following tasks could be considered:

1. intersect the three polygons
2. Add to these points the corners of both polygons
3. create an irregular triangulated network
4. remove triangles that do not contain any lidar point or very few lidar points taking into account their surface
5. collect the outer edges of the network
6. Improve outline by comparing it with polygon of outer points.

To determine the appropriate corners of outlines, another aspect that can also be used is the intersection of sloped roof faces adjacent to building edges with an horizontal plane.



Building A35 - Strategy 1	Building A35 - Strategy 3

Figure 6-2: Combination of strategies

- Detect and correct for missing data by looking for empty area adjacent to buildings that do not contain any ground or tree point.

- Implement the strategy in C++ with the use of a compiler instead of an interpreter in order to make it quicker. Meanwhile, design a k-d tree to make easier access to points.

- Offer to the user a possibility of semi-automatic method in addition to the automatic procedure because the results obtained are sensitive to the tuning of thresholds used in the algorithm. Thus, it can be created an interface where tuning the parameters will be possible in case the user is not satisfied with the automatic results. Also this interface should offer the possibility to choose among the outlines computed with the different strategies or to manually edit the obtained outlines.

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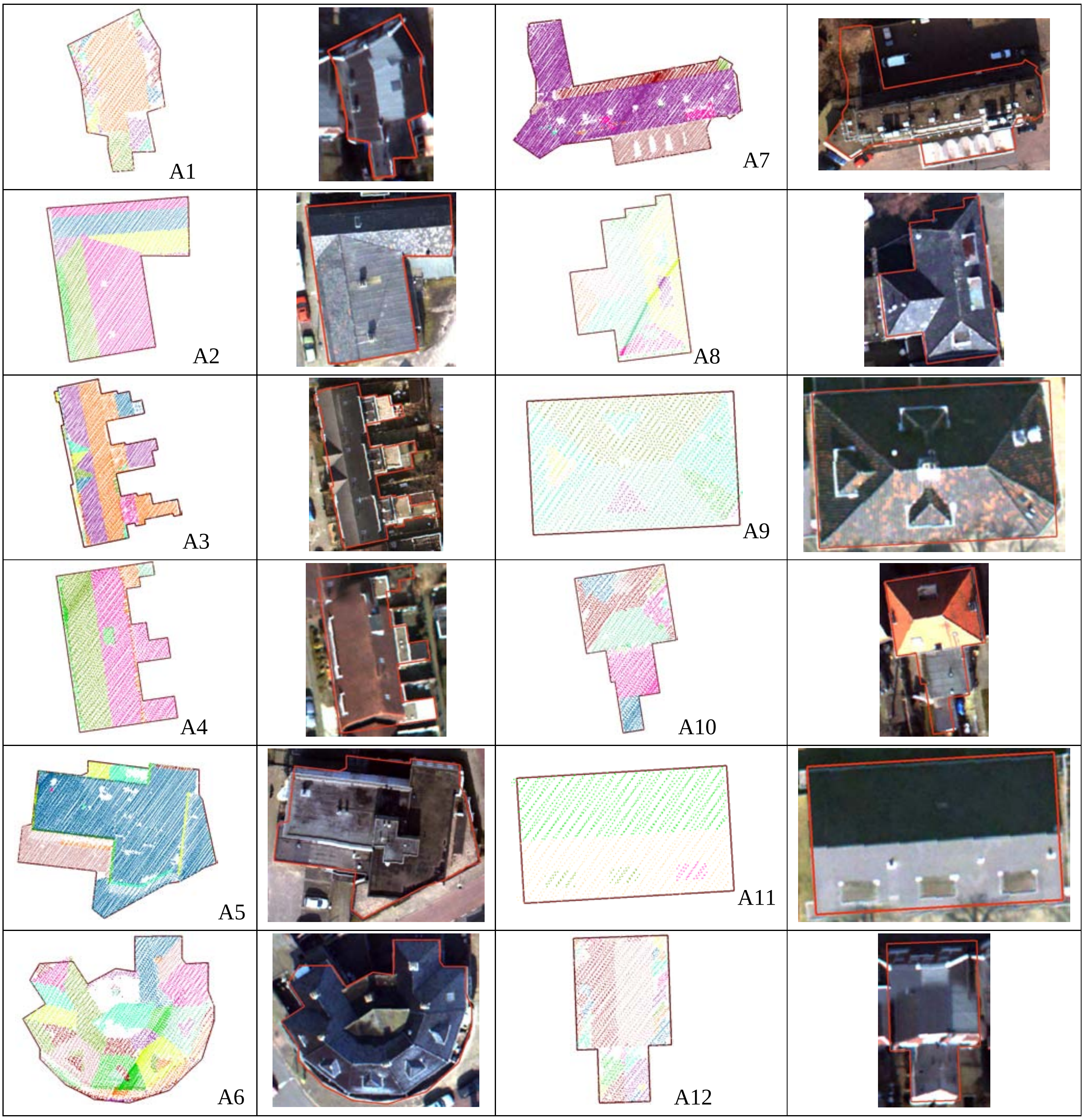
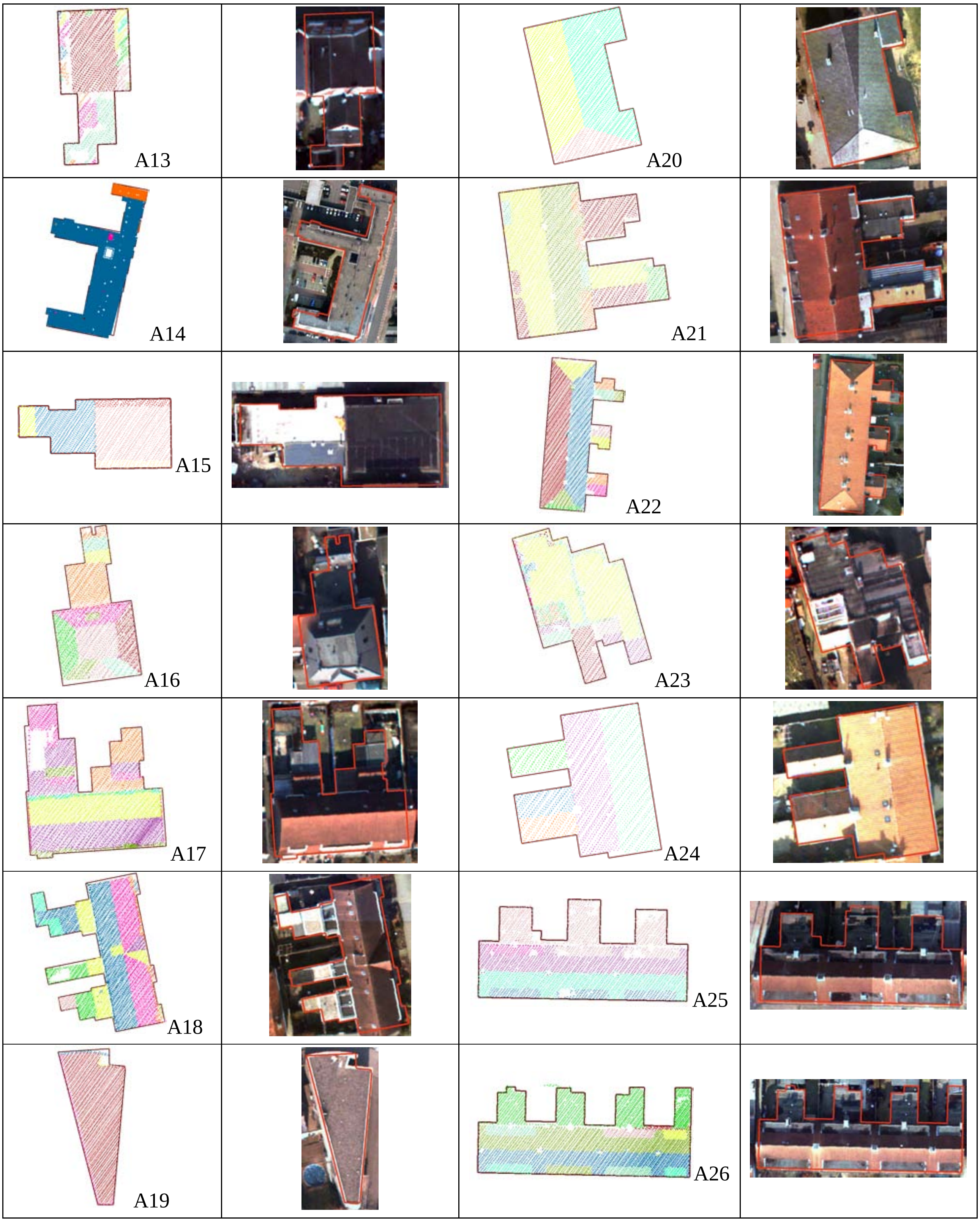
Appendix A: Computed outlines superposed with point clouds coloured by segment and with orthoimages

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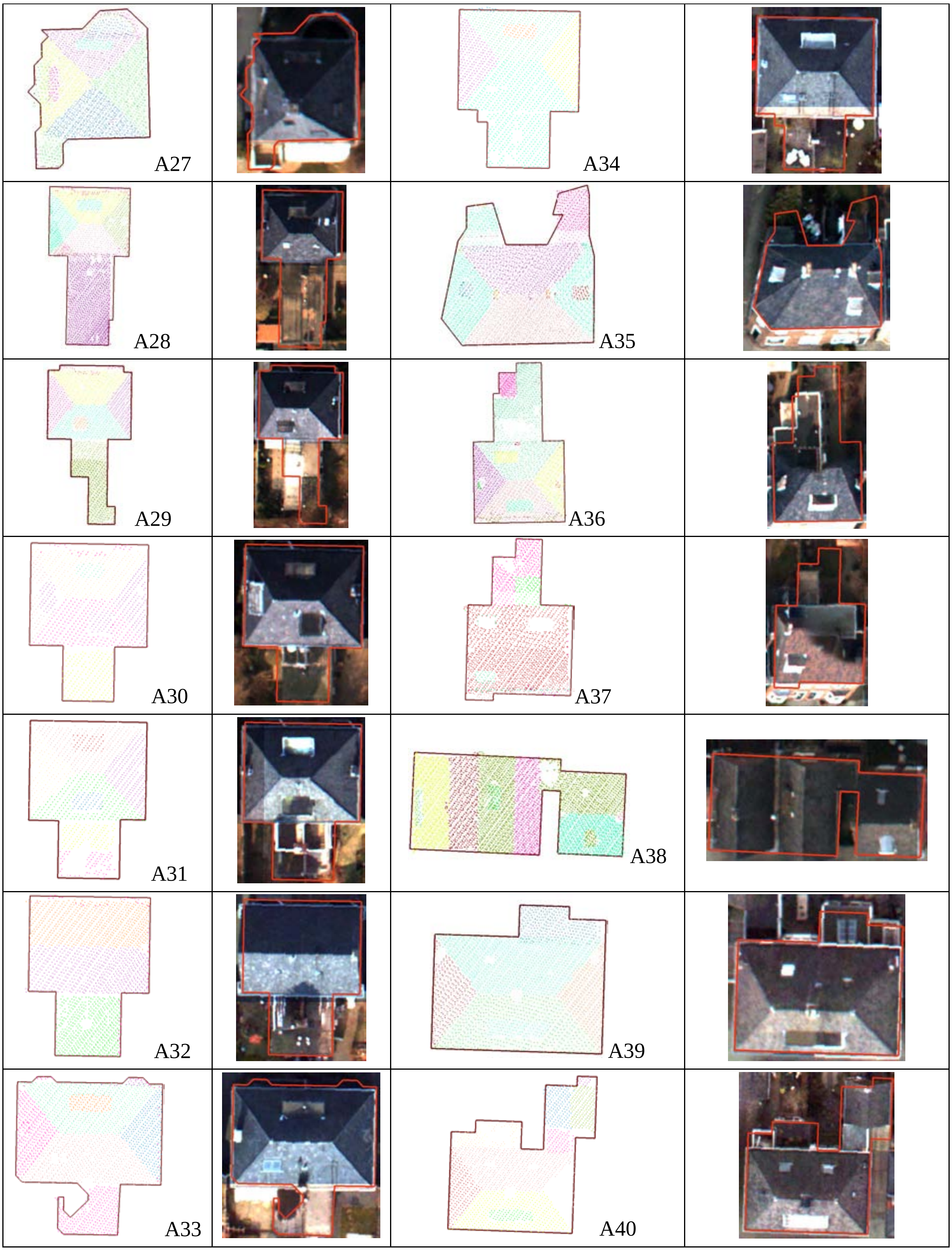
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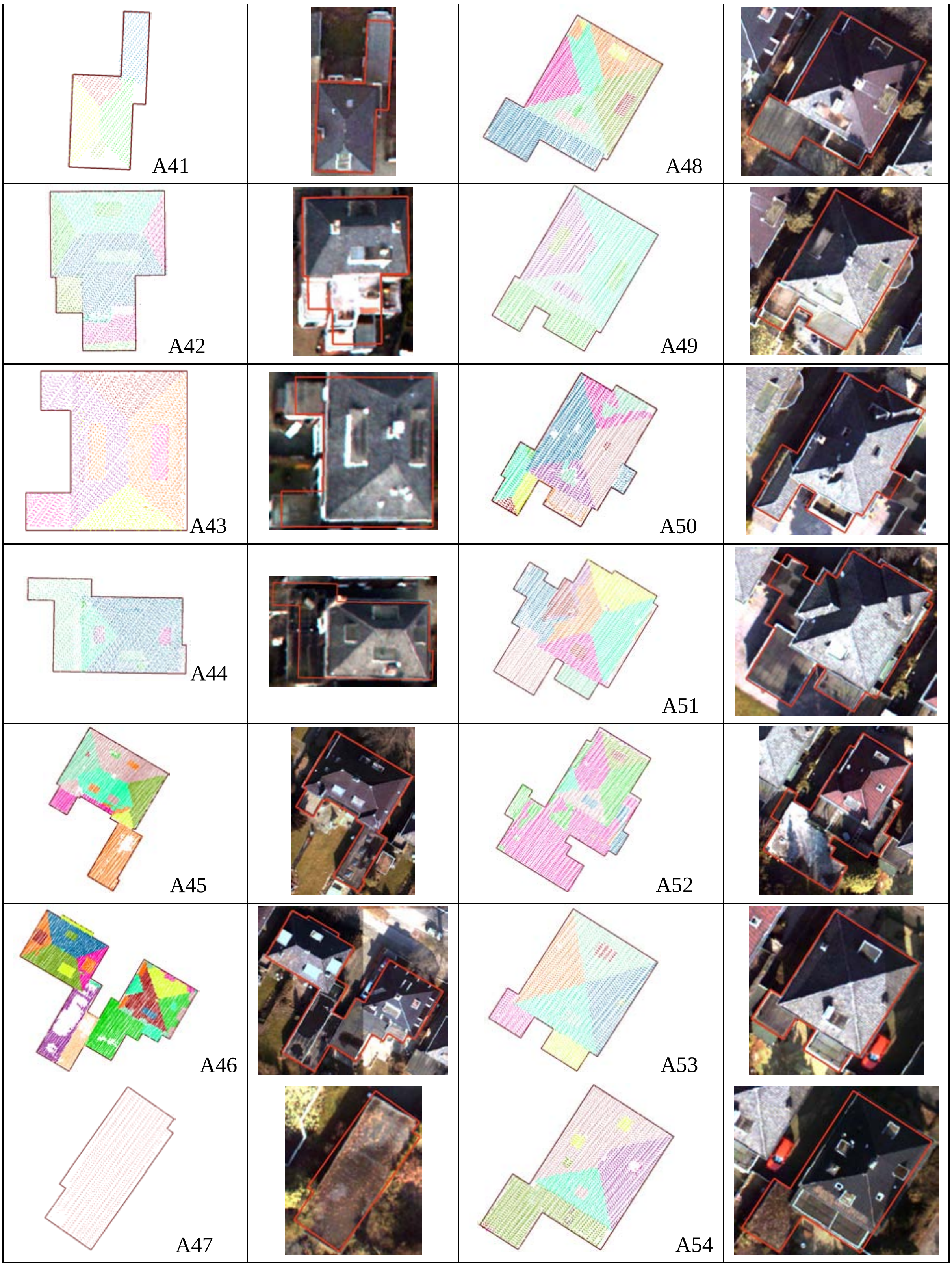
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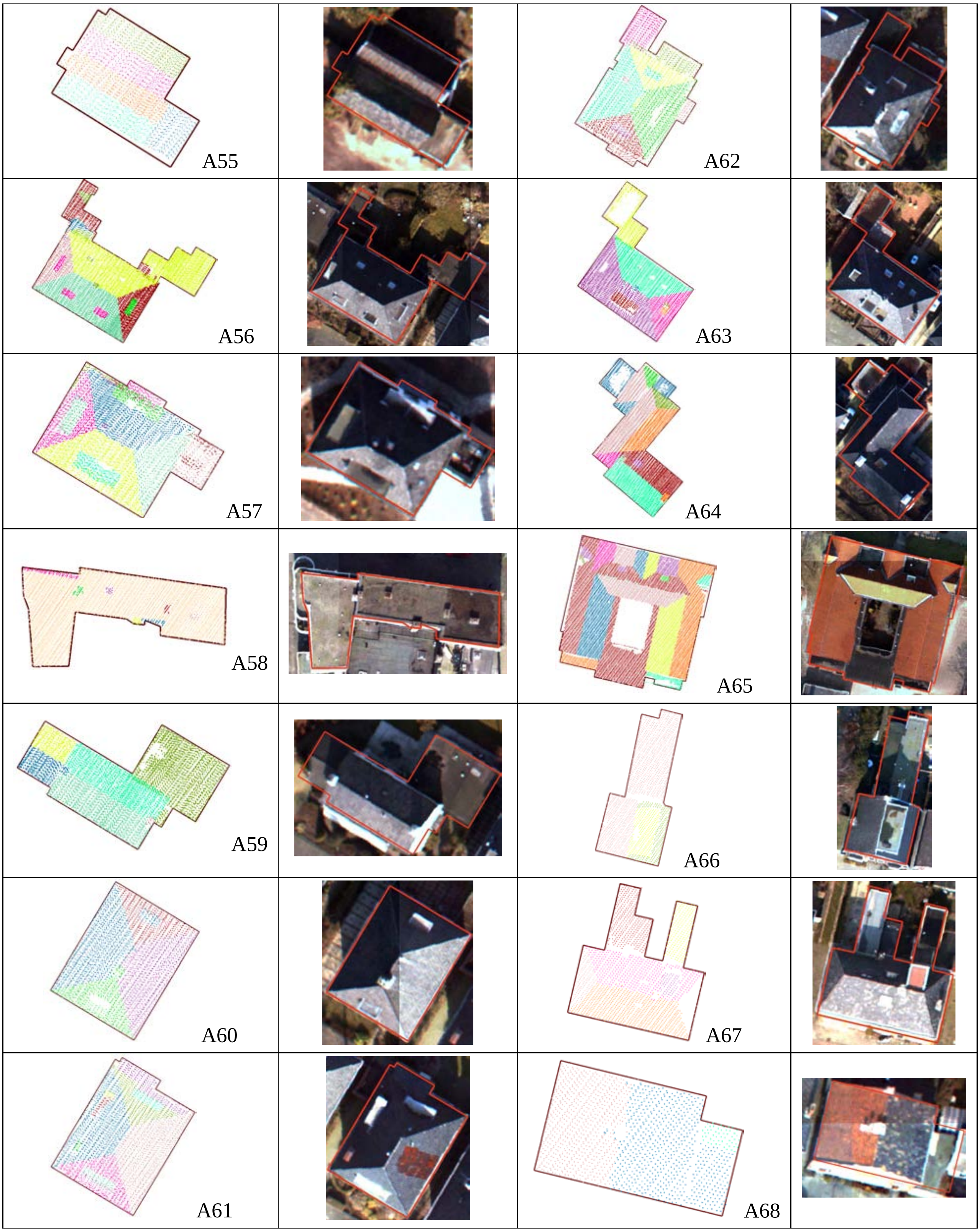
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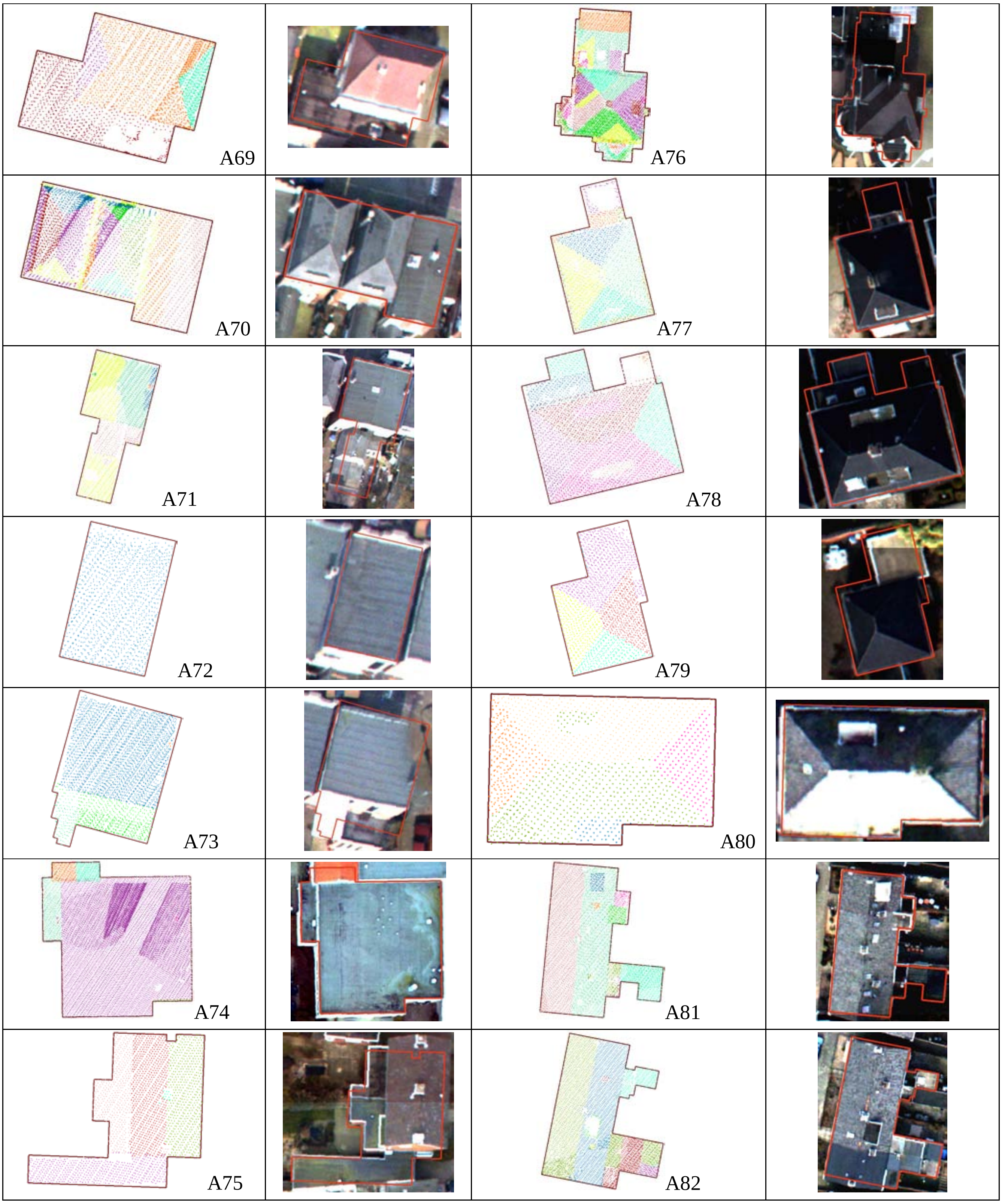
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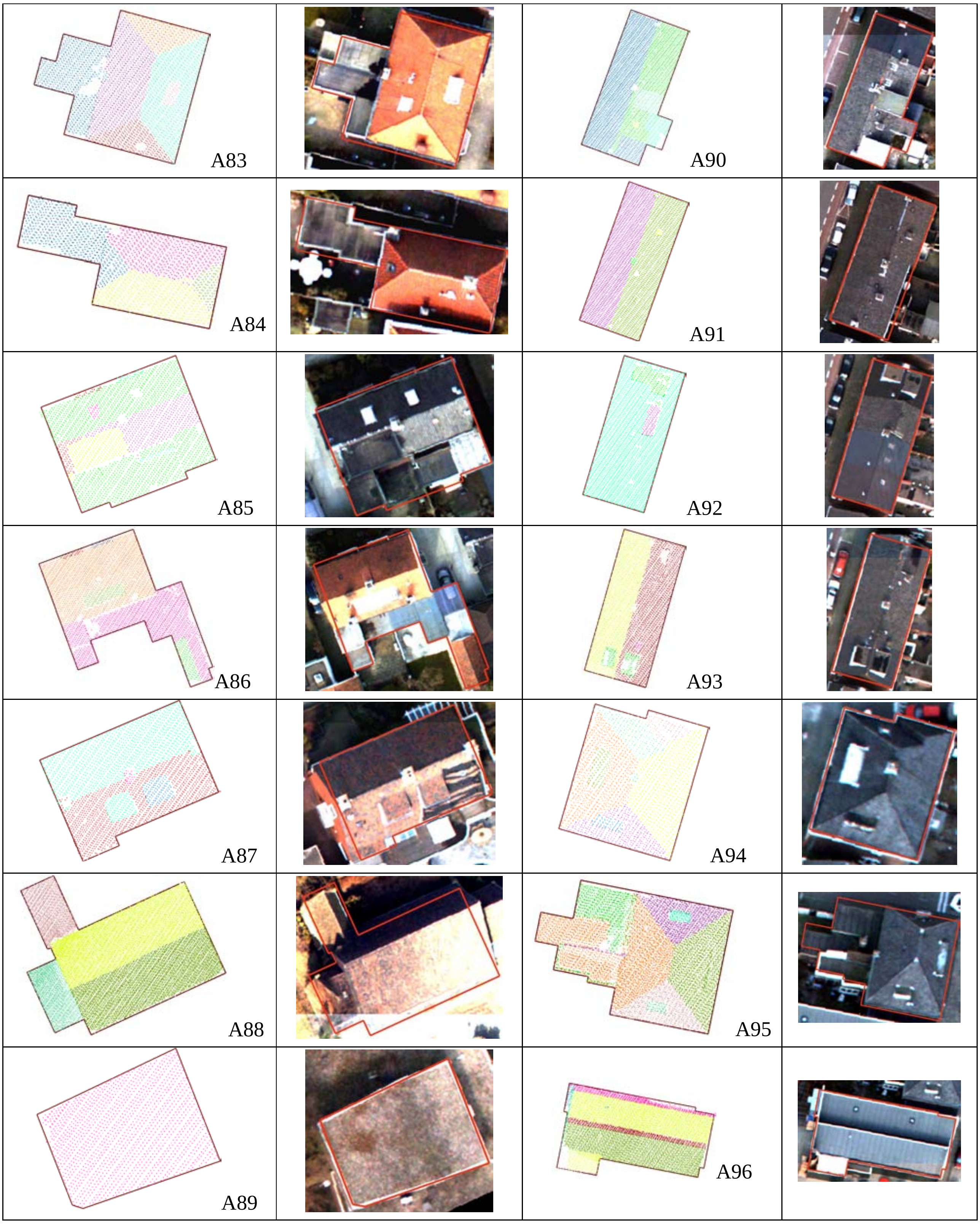
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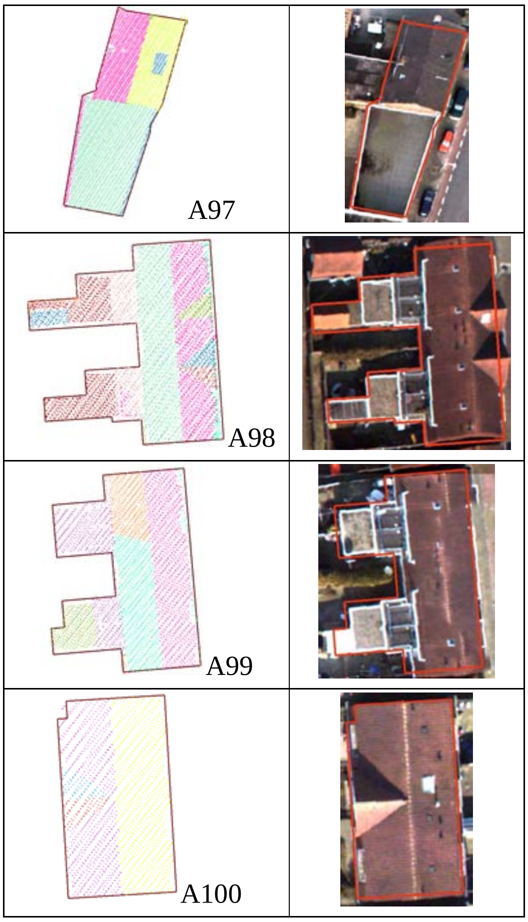
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Appendix B: Visual Comparison between designed approach and method implemented in the software Point Cloud Mapper

A= Building Number
B= Correct general shape with required number of corners
C= Correct general shape with fewer or higher number of corners
D= Incorrect shape
E= Fail to be computed

	[Vosselman, 1999] Approach				Current Approach			
A	**B**	**C**	**D**	**E**	**B**	**C**	**D**	**E**
A1			■			■		
A2		■			■			
A3		■				■		
A4		■			■			
A5		■				■		
A6		■				■		
A7		■				■		
A8	■					■		
A9		■				■		
A10		■			■			
A11	■				■			
A12	■				■			
A13		■			■			
A14		■				■		
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Appendix C: Quantitative Performance analysis results

A= Building Number
B= Outline reconstruction strategy
C= Percentage of points inside outline (%)
D= Difference in Number of corners between computed and reference outlines
E= Difference in Main Orientation (degrees)
F= Extra Difference Area (%)
G= Missing Difference Area (%)
H= Average distance between outlines (Precision of outline) (cm)

(A positive value in this table for parameters D to J indicates that it is higher than it should be)

A	B	C	D	E	F	G	H
A1	3	99.17	2		2.52	0.95	8.98
A2	3	99.71	2		0.91	0.44	5.4
A3	1	99.42	-1	-1.35	5.07	1.56	19.06
A4	1	99.8	0	-0.16	0.62	0.61	3.37
A5	3	99.84	3		1.1	0.26	8.15
A6	3	99.48	-3		1.71	0.6	9.85
A7	3	99.54	-7		1.3	0.8	8.8
A8	1	99.19	4	-0.11	2.56	0.92	8.25
A9	1	99.44	-1	0.65	3.25	0.33	11.32
A10	1	99.72	0	-1.32	2.66	0.47	7.9
A11	1	99.83	0	0.63	0.86	1.22	6.02
A12	1	99.77	0	-1.1	2.37	0.3	7.08
A13	1	99.46	0	-0.25	1.75	1.33	7.41
A14	1	99.86	-1	0.01	1.42	0.86	14.73
A15	1	99.4	0	-0.15	0.38	1.21	4.34
A16	1	99.44	4	-4.07	3.56	0.97	12.39
A17	1	99.63	1	-0.31	1.87	0.98	9.04
A18	1	99.44	-1	-1.83	2.7	0.95	9.05
A19	3	99.86	-2		2.63	0.08	7.98
A20	1	99.65	-1	0.33	1.59	0.29	6.53
A21	1	99.77	0	-0.47	2.2	0.14	7
A22	1	99.49	-8	0.41	3.53	0.3	10.99
A23	1	99.41	1	0.12	1.28	1.31	7.3
A24	1	99.38	2	-1.23	3.25	1.43	11.7

A25	1	99.44	4	0.13	1.17	0.51	5.13
A26	1	99.32	0	0.03	1.62	0.36	5.77
A27	2	98.95	4	-2.68	3.53	1.67	10.97
A28	1	99.48	-6	1.22	4.59	1.63	16.73
A29	1	99.21	-4	0.74	2.6	1.19	8.61
A30	1	98.82	-8	0.95	4.62	1.16	14.64
A31	1	96.86	-8	0.56	7.21	0.42	20.96
A32	1	98.99	-8	0.91	3.4	0.64	10.29
A33	2	99.23	8	1.04	0.8	4.45	13.86
A34	1	99.05	2	0.94	1.91	1.82	10.11
A35	3	98.53	5		1.81	1.77	9.08
A36	1	98.88	0	-0.92	2.73	0.22	7.69
A37	1	98.06	-2	1.49	3.85	0.47	10.58
A38	1	98.91	-6	1.2	3.28	1.3	11.21
A39	1	99.41	-2	0.21	1.47	0.08	4.51
A40	1	99.13	-4	0.33	2.43	0.57	7.98
A41	1	98.93	0	0.16	5.47	1.61	12.8
A42	1	99.05	0	-0.45	3.41	0.48	11.03
A43	1	99.86	-4	-0.96	3.36	0.31	9.84
A44	1	99.44	-2	0.98	1.83	1.36	7.38
A45	1	99.73	2	0.19	0.48	1.31	5.47
A46	1	99.76	0	-0.69	1.09	1.19	8.06
A47	1	98.89	4	1.93	5.47	3.05	18.07
A48	1	99.74	0	-0.18	0.76	0.48	3.78
A49	1	99.54	0	-0.44	0.9	2.16	8.44
A50	1	99.55	-4	0.23	3.35	0.94	9.84
A51	1	99.59	-4	-1.18	2.65	1.03	10.68
A52	1	98.67	2	-1.72	0.72	2.42	8.73
A53	1	99.55	0	-0.18	0.1	1.58	4.35
A54	1	99.69	0	-0.08	1.95	0.42	6.65
A55	1	99.08	6	2.36	4.41	1.91	11.45
A56	1	99.65	6	-0.07	1.72	1	6.84
A57	1	99.81	0	0.13	1.9	0.6	5.79
A58	3	99.49	0		1.23	0.45	4.7
A59	1	99.73	-2	-0.67	1.86	1.14	6.83
A60	1	99.76	0	-0.93	1.56	0.12	4.5
A61	1	99.88	0	0.34	1.49	1.51	8.39
A62	1	99.24	4	1.45	0.73	1.78	5.51
A63	1	99.8	-2	0.66	1.8	1.24	9.03
A64	1	99.21	0	-0.2	0.54	1.99	7.84
A65	1	99.81	2	1.08	1.77	1.03	24.41
A66	2	99.5	1	-0.07	0.83	1.71	6.38
A67	1	98.81	0	0.33	12.5	1.27	33.9

A68	1	99.47	0	1.68	2.88	0.5	8.21
A69	1	99.75	0	-1.16	2.14	0.36	6.13
A70	1	99.77	0	0.03	2.24	0.03	7.23
A71	1	99.53	2	0.35	4.06	1.17	14.62
A72	1	99.64	0	0.01	3	1.04	7.37
A73	1	99.41	3	2.62	7.68	0.48	20.96
A74	1	99.79	0	-0.73	1.18	0.23	7.64
A75	1	99.43	2	1.97	1.26	2.08	7.77
A76	1	99.56	10	0.19	3.55	1.2	15.62
A77	1	99.86	0	0.57	2.88	0.57	8.12
A78	1	99.72	-2	0.2	2.81	0.39	9.36
A79	1	99.36	-4	-0.51	3.67	0.75	8.01
A80	1	99.4	0	0.52	1.3	1.52	6.43
A81	1	99.5	0	-0.46	1.27	0.43	4.79
A82	1	99.56	4	-0.07	2.35	0.25	7.96
A83	1	99.48	-2	0.07	0.91	0.9	4.84
A84	1	99.19	-6	0.11	5.42	0.67	10.66
A85	1	99.44	-12	2.04	3.08	0.89	12.03
A86	1	99.11	1	0.57	1.03	0.99	5.19
A87	1	98.99	0	-0.32	2.52	0.03	7.52
A88	1	99.88	0	0.03	1.92	0.27	9.54
A89	3	99.8	0		4.31	0.34	11.82
A90	1	99.8	-2	0.15	1.9	0.42	7.45
A91	1	99.71	0	-0.02	1.34	0.78	6.94
A92	1	99.49	-1	-0.29	1.54	0.11	5.5
A93	1	99.9	0	-0.31	1.38	0.3	5.59
A94	1	99.64	0	1.05	0.93	0.88	5.43
A95	1	99.83	-2	0.65	2.33	0.52	9.06
A96	1	99.79	4	-0.18	1.37	1.26	9.56
A97	3	99.3	3		0.33	1.28	6.02
A98	1	99.51	-6	0.03	1.61	0.71	5.91
A99	1	98.8	-8	0.89	3.54	2.01	15.34
A100	1	99.57	2	-0.44	3.34	0.73	11.8