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# Using photogrammetric Digital Surface Model in LiDAR software for creating Three Dimensional Buildings

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## **Abstract**

The way of representing Earth has changed; two dimensional (2D) maps have turned into three Dimensional (3D) representations. There are many studies in order to create 3D city maps as well as areas where these are applied such as 3D cadastral, 3D visualization and flood simulation, etc. These can be created with the aid of different data sources using photogrammetric Digital Surface Model (DSM) derived from image matching and from Light Detection and Ranging (LiDAR) point clouds or both of them combining orthophotos and building footprints. Several software has been developed to ease and speed up this process.

In this study, a current state-of-the art in the 3D city modeling with particular interest to commercial software was analyzed. DSMs from image matching (Satellite and Airborne) were used in order to create a 3D city model of Trento, Italy. The objective was to examine the degree of automation and the computation time of two available software: Feature Manipulation Engine (FME) and Building Reconstruction (BREC). Other problem such as the quality of the DSM needed would be discussed for each software and the results would be compared to those achieved using LiDAR data. Recommendations and possible problems would also be addressed.

In order to create a 3D city model, the ALDPAT software (Airborne LiDAR Data Processing and Analysis Tool) has been used to separate the ground regions (Digital Terrain Model, DTM) from the man-made objects and trees (Normal Digital Surface Model, nDSM). FME and BREC software have been used to reconstruct the 3D city model.

The output results from FME and BREC have been analyzed qualitatively and quantitatively. The comparison between the models generated from photogrammetric and LiDAR DSMs have been performed. The results show that buildings generated by satellite images have poorest quality compared with buildings from LiDAR and airborne data.

In particular, the performed tests will be shown that among the Level of Details (LoD), a LoD1 and LoD2 3D city models can be generated using a DSM by image matching. A deeper study should be done in order to analyze the level of detail qualitatively.

Key words: 3D city modeling, ALDPAT, BREC, FME, DSM, DTM

## **Preface**

This thesis is the outcome of the final project for a degree in Geomatics at the University of Gävle, Sweden and as part of the degree at the University of Extremadura, Spain.

This thesis would not be possible without those who supported me during the project period. I would like to thank all the people who contributed either directly or indirectly to this work. However, there are a few people who I would like to specifically mention here. First of all, my sincere gratitude to my supervisors, Nancy Joy Lim, Fabio Remondino and Francesco Nex for their guidance in this project. I would like to thank to Dipl.-Ing. Dominik Schroll and virtualcitySYSTEMS GmbH for the trial version of the software Building Reconstruction. I would also like to utter my gratitude to the entire 3D Optical Metrology unit of the Bruno Kessler Foundation (FBK) of Trento (Italy) for the input data and the advices received during my period in Trento. Also, special thanks to my friends. Finally, I thank my family for all the support and encouragement they had given me during my studies.

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## LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
ALDPAT	Airborne LiDAR Data Processing and Analysis Tool
BREC	Building Reconstruction
DSM	Digital Surface Model
DTM	Digital Terrain Model
FME	Feature Manipulation Engine
LiDAR	Light Detection And Ranging
LoD	Level of Detail
nDSM	Normal Digital Surface Model

# 1. Introduction

## 1.1. Background

The way of representing Earth has changed with the fast growth of technologies. Two-dimensional (2D) maps have turned from the traditional paper-based to digital forms, and from planar 2D to a three-dimensional (3D) representation of objects. Among the different cartographic products, 3D city models have shown to be valuable instruments for several applications such as urban planning and city management, 3D cadastre, flood simulations, land monitoring, mobile telecommunication, 3D visualization, solar radiation potential assessment, etc. (Tack, Buyuksalih, & Goossens, 2012)

There are several options to obtain data for 3D maps and models (Remondino, 2011). One possibility is to use image data processed with photogrammetric methods. Photogrammetry provides precise, reliable and detailed 3D information that can be used for mapping and 3D modeling applications (Suveg & Vosselman, 2004). Images can be taken using satellite, aerial airborne, unmanned aerial vehicle (UAV) (Cai, Feng, Chen, & Lee, 2008) or terrestrial sensors according to the required geometric resolution and field-of- application. An alternative to photogrammetry is Light Detection And Ranging (LiDAR), which allows a quick derivation of 3D information, however, it is expensive.

Depending on the data and their quality, 3D models can be produced in different levels-of-detail or LoDs (Kolbe, Gröger, & Plümer, 2005; Haala & Brenner, 1999). Unfortunately, the total automation of a detailed and accurate 3D city model is not yet possible. In order to reduce manual work that requires time, a set of reliable data and an experienced user, semiautomatic methods like photogrammetry, Digital Surface Model (DSM) or point clouds derived from image matching and LiDAR, and a combination of these data with cadastral footprint and orthophotos (hybrid sensors), have been proposed. Nonetheless, 3D city model automation is needed because manual and semi-automatic techniques are still costly and time-consuming (Haala & Brenner, 1999; Hu, You, & Ulrich, 2003).

Several commercial software packages for man-made feature extraction and 3D reconstruction have been developed in the last years, in order to simplify the operators' works. However, most of them have focused on LiDAR data as an input for many reasons. Firstly, DSM from LiDAR is automatically generated with high quality, accuracy and density. Secondly, photogrammetric point clouds or DSM provide geometric information, as opposed to LiDAR data, which contains multi-eco pulses or intensity information. Thirdly, DSM from photogrammetry comes with blunders/noise and some gaps in the point cloud due to image dissimilarities, occlusion, shadow and steep changes in slope that can produce incorrect reconstruction (Tack, Buyuksalih, & Goossens, 2012; Vallet and Aguiaro, Poli, & Remondino, 2012).

Building reconstruction based on aerial imagery can extract the geometric properties of buildings from DSM produced by image matching ( Haala & Brenner, 1999; Aguiaro, Poli & Remondino, 2012). There are algorithms for 3D modeling of buildings that extract the roofs' geometry, which are the only parts visible from airborne photogrammetric and remote sensing data. There are also algorithms that filter or classify ground and non-ground data from DSM using mainly LiDAR data, although

some of them can be used with photogrammetric DSM (Zhang & Whitman, 2005; Sithole & Vosselman, 2004; Axelsson, 2000).

Photogrammetric data can be an alternative method to LiDAR point clouds to reconstruct 3D building because some photogrammetric software can derive density point clouds using image matching. Furthermore, 3D city model generation is still an open research issue that is demanded and interesting for many areas. Besides, it is a timely topic for many researchers, who are trying to increase the automation and reliability of this process (Nex & Remondino, 2012).

### **1.2. Aims of the study**

The study aims to evaluate the different typologies of photogrammetric DSM derived from satellite and airborne images, by using and comparing different software that are typically used for filtering and processing LiDAR data and reconstructing 3D buildings. The specific objectives of this research are as follows:

1. Evaluate in a more systematic and complete way, what the current-state-of-the-art in the 3D city modeling is, especially in commercial software.
2. Analyze different parameters such as the degree of automation and the computational time of each commercial solution focusing on LiDAR data, when applied to photogrammetric DSM.
3. Compare what the most appropriate typology of input data (aerial, satellite images, LiDAR) is, according to the requested level-of-detail of the city model.
4. Describe problems found with DSMs used with LiDAR software.

The LiDAR software that are going to be evaluated with photogrammetric DSM data are Airborne LiDAR Data Processing and Analysis Tools (ALDPAT), Building Reconstruction (BREC), and Feature Manipulation Engine (FME). The evaluation will be carried out on the 3D city models that will be generated in different LoD.

The research's output 3D models that will be generated will be useful to identify what is the most appropriate input data to create a 3D model of the whole municipality of Trento to be used for planning, as well as in different projects where the 3D city model can be necessary beside for simple visualization purposes.

### **1.3. Organization of the thesis**

The organization of the thesis is structured as follows:

Section 1 presents an introduction to the project. It outlines the state of the 3D building reconstruction thought different typology of DSM, presents the scope and the objectives.

Section 2 presents the previous studies through a literature review, which shows firstly the classification of the different levels-of-detail, secondly the current status of the 3D building reconstruction with different data and most specifically from DSM, and finally a review of the available software for 3D city reconstruction.

Section 3 describes the methods conducted in the thesis.

Section 4 presents the results.

Section 5 discusses the results.

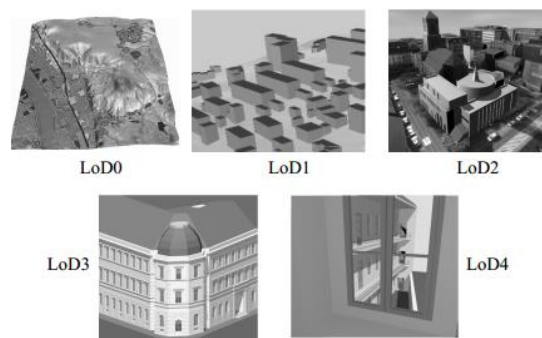
Section 6 presents the conclusion arrived in the thesis.

## 2. Previous Research in the art of 3D city modeling

This section deals with a literature review, which examines the current status of 3D city modeling made out of different data sources, especially those that stem from DSM. In order to provide appropriate background information of this area, the classification of the different levels-of-details in 3D city modeling will be presented first. Then, the current status of the reconstruction of 3D city from different data sources will be shown, and more specifically, the building reconstruction of 3D city model from DSM will be studied. Finally, there will be a brief review of some available software for building reconstruction.

### 2.1. The level-of-detail (LoD) in the art of 3D city modeling

3D city model is mainly composed of buildings that can be modeled differently depending on different levels-of-details. The Open Geospatial Consortium (OGC) has adopted City Geography Markup Language (CityGML) as a standard for modeling urban and man-made objects. CityGML classifies five LoDs as shown in Figure 1. The first level is indicated as LoD0 and contains the Digital Terrain Model (DTM). LoD1 represents buildings in block models, while LoD2 includes different elements like roofs, surfaces or, material, for instance. LoD3 is composed of high resolution textures, and detailed wall and roof structures, windows, doors, and balconies, creating an architectural level. The last level is LoD4, which adds more detailed objects to LoD3 as rooms, partitions, doors, stairs, furniture, electricity units, ventilation units and decorative parts to the interior of the buildings (Kolbe, Gröger, & Plümer, 2005).



**Figure 1.** The five Levels-of-Detail (LoD) in CityGML (Kolbe, Gröger, & Plümer, 2005)

The LoDs in 3D building reconstruction depend on the data source and their characteristics, apart from the building extraction techniques. The highest LoD using DSM from airborne and satellite image has either been created in LoD1 or LoD2, with automatic or semi-automatic procedures. Increasing the LoD reduces the automation considerably (Tack, Buyuksalih, & Goossens, 2012; Chikomo, Mills, & Barr, 2007).

## 2.2. 3D city model reconstruction

The reconstruction of a 3D city model can be performed with the aid of different data sources such as satellite and airborne images, DSMs derived from LiDAR or photogrammetric image matching, or a combination of these with cartographic and cadastral maps. According to Kabolizade, Ebadi and Mohammadzadeh (2012) the reconstruction of buildings includes: (i) building detection; (ii) extraction; and, (iii) reconstruction. Building reconstruction is a process to generate the 3D model through features obtained from building detection and extraction. By using an image, the buildings are extracted by detecting their edges with their radiometric characteristics, and by doing an automatic or manual classification. Buildings are also extracted by using the DSM derived from image matching photogrammetric procedures or LiDAR, using several algorithms for extracting, classifying or filtering. However, most of them are focused on LiDAR data (Zhang, Chen, Whitman, Shyu, Yan, & Zhang, 2003; Zhang & Whitman, 2005; Sithole & Vosselman, 2004).

Automatic and semi-automatic techniques have been developed to generate 3D city models. Semi-automatic process means that the user makes part of the reconstruction, while in the automatic method, the 3D model is generated by the software (Hu, You, & Ulrich, 2003; Suveg & Vosselman, 2004). Representing 3D model is not an easy task. It is time consuming and requires highly qualified personal and expensive instruments. Thus, the automation to create 3D models is needed, but it is not yet a reality (Suveg & Vosselman, 2004). To obtain an automatic 3D reconstruction of buildings, some researchers proposed that automatic and semi-automatic methods should use several data sources such as optical airborne, spaceborne, UAV, LiDAR or Airborne Laser Scanning (ALS), microwave imaging sensors, cartographic and cadastral maps (Sohn & Dowman, 2007; Kraus, Lehner, & Reinartz, 2007; Poli, Wolff, & Gruen, 2009; Haala & Brenner, 1999; Tack, Buyuksalih, & Goossens, 2012).

In Kraus, Lehner and Reinartz (2007), a process for extracting 3D city models automatically from very high resolution (VHR) stereo satellite images like Ikonos was found. They created a DSM derived from DTM and these were also used to create a true orthophoto. Then a classification was made with the aid of the DSM, DTM, orthophoto and the Rational Polynomial Coefficient (RPC) available in the metadata of the image. Based on the classification, the borders of the objects were extracted and they were modeled as ground, tree, and building objects. Finally the model was represented through geometric primitives and exported in 3D obtaining an LoD1. They argue that the process has to be further developed, but this method has already refined the steps for automation in order to generate 3D city models.

Poli, Wolff, & Gruen (2009) extracted 3D city models from DSM and evaluated the VHR satellite image worldview-1 with 50 cm resolution data. They analyzed the radiometric characteristics and accurate orientation of the image. They compared the worldview-1 of the DSM with an aerial image DSM in order to evaluate the quality differences. To extract the 3D model of the stereo pair, the software CyberCity Modeler was used. They concluded that this sensor is a highly potential means for 3D modeling and generating a 3D model of the area in LOD2.

The most common methods to reconstruct 3D cities are the combination of different data sources. Haala and Brenner (1999) combined multispectral imagery and laser altimetry data for the extraction of buildings, trees and grass-covered areas, while in

obtaining the reconstruction of the buildings, they used laser data and 2D ground plan information. Another possible combination of data was applied by Suveg and Vosselman (2004), who analyzed aerial image with the aid of information from a large-scale 2D Geographic Information System (GIS).

In recent years, the integration of LiDAR data and photogrammetric data has been considered, and image matching process to generate DSM from photogrammetry has been improved (Tack, Buyuksalih, & Goossens, 2012).

A Digital Surface Model can be obtained from image matching photogrammetric procedures or directly from LiDAR data. According to Poli and Caravaggi (2012), “Image matching have aims at finding dense and robust correspondences between stereo images and estimate their 3D coordinates in object space.” In the building reconstruction from DSM, some special terminology is used. Digital Surface Model has both the ground (i.e. Digital Terrain Model, DTM) and the normal Digital Surface Model (nDSM), which includes non-ground elements (buildings, trees, shadows, etc.).

3D building reconstruction studies are mainly done with LiDAR data due to the quick acquisition of the DSM from the pulse of the light, and its better accuracy (Tack, Buyuksalih, & Goossens, 2012). A few approaches are performed using DSM derived from image matching because it has just the geometric property. However, in recent years, airborne and satellite images have increased their spatial resolution and the software for image matching have improved, deriving better result (Suveg & Vosselman, 2004; Kraus, Lehner, & Reinartz, 2007; Vallet, Pierrot-Deseilligny, Boldo, & Brédif, 2011; Poli & Caravaggi, 2012).

The result of creating a 3D city model with photogrammetric procedure depends on the Ground Sample Distance (GSD), which derives DSM for reconstructing city models in different levels-of-detail. Nex and Remondino (2012) argue that image matching can generate denser point clouds than LiDAR data. They also mentioned that in theory, “an image block with a GSD of 10 cm would allow the derivation of a point cloud with 100 points/m<sup>2</sup>. A typical LiDAR flight for city-modeling applications is in the order of 15-20 points/m<sup>2</sup>”. Oude Elberink and Vosselman, (2011) argue that the extraction of a higher number of object points allows discontinuities, defining in a better way the geometric modeling

### **2.3. Software for 3D city reconstruction**

Several software using manual, semi-automatic and automatic methods have been developed in order to generate 3D city reconstruction. The data used in them can be DSMs, especially from LiDAR, but also from photogrammetric image matching, in combination with other sources such as orthophotos, images and cadastral footprints. Most commercial software used for building reconstructions from DSM are TerraScan, VirtualGrid, Erdas, Building Reconstruction (BREC) and Feature Manipulation Engine (FME). Only a brief description of each software is given below. An extended description of them can be found in their user manuals.

**Terra Scan** is a software, that generates 3D city model in LoD1 and LoD2 from raw LiDAR point cloud (Terra Solid, 2012).

**VirtualGrid** creates 3D city models in LoD1 and LoD2 using LiDAR (VirtualGrid, 2012).

**Erdas** reconstructs the building in 3D, manually, using stereoscopic visualization (Intergraph Corporation Part of Hexagon Group, 2012).

**Building Reconstruction (Brec)** is a software, that generates 3D building models in LoD1 and LoD2 with DTM and DSM from airborne LiDAR and 2D buildings (e.g. cadastral footprints) as input data. The outputs of the software are CityGML (\*.gml) and Esri shapefile (\*.shp), and can be visualized in any software that supports 3D data such as FME and ArcScene. The LiDAR data need to have as minimum 1 meter raster cell size but 2 meter raster cell size is sufficient for extracting building heights. The result can be reconstructed in the software, and be edited and refined using the DSM point cloud by adapting the model to the DSM (virtualcitySYSTEMS, 2012).

## **FME**

FME (Feature Manipulation Engine) is a software that translates geographic data to a different format and works with transformers to manipulate data. FME 2012 includes 400 different transformers to carry out different types of restructuring (SafeSoftware, 2012a).

### **3. Study area, data description and software**

In this section the study area, the data and the software used for this study are presented. First, an introduction of the study area is explained. Secondly, a description of the data used in this thesis is drawn. Finally, the software employed in this thesis is also describe.

#### **3.1. Study area**

The city of Trento is located in the north of Italy in the Trentino Alto Adige region which is formed by the Autonomous Province of Trento and Bolzano. Trento is the capital of the mentioned region as well as the Autonomous Province of Trento. The geographical coordinates and the altitude, with reference the sea level, approximate where is located are 46°4'0"N 11°7'0"E y 190 m respectively. Its population according to the National Institute of Statistics in the end of November of 2012 is 115.368 inhabitants and has an area of 157 km<sup>2</sup>, being so its population density of 735 inhabitants per km<sup>2</sup> (EGN, 2013; Demoistat, 2013).

Trento lies in the Adige glacial valley and is surrounded by the Alps. The structure of the city is very irregular. In the center of the city there are historic buildings with different shapes and heights. In the outskirts of the center we can find areas of rocky areas besides agriculture. The main river that crosses the city is the river Adige. Furthermore, it is a city with history; this can be seen in their different buildings around the city from different eras such as roman, medieval, renaissance, baroque, and modern. This city is well known for the Council of Trento (Trentocultura, 2013; Comune.trento, 2013).

Trento and its surrounding is a tourist area throughout the year. In summer recreational activities such as climbing and biking trails and in winter many tourists come to visit the ski pistes (Visittrentino, 2013). Furthermore, tourists not only come to Trento to enjoy outdoor sports. It also comes for its many events held in this city such as Festival

dell'Economia, Trento Film Festival, Feste Vigiliane, etc (Festivaleconomia, 2013; Festevigiliane, 2013).

This city was chosen as a study area because there was a study done on it over the DSM derived from satellite imagery (Agugiario, Poli, & Remondino, 2012). For that, in this thesis we want to see whether it was valid to 3D models from this previous data using the software available on the market. Furthermore, this 3D model want to be compared with other models derived from DSM with more accurate mesh resolutions such as a photogrammetric flight or a flight LiDAR system.

Within the city, a study area was chosen because of its special characteristics. This area is located in the city center. It was chosen because it was a recognizable land area with little vegetation (the cemetery of Trento) in addition to a building with great volume and easy to recognize. (Figure 2)



**Figure 2.** Map of the study area (OpenStreetMap, 2012)

### 3.2. Data

For this study, three point clouds (or DSM), cadastral maps, and orthophotos had been used.

The three DSMs that were provided by FBK-3DOM, are: 1) DSM derived from LiDAR flight (2 x 2 km tiles) at 1 m grid resolution; 2) DSM derived from photogrammetric procedures using the software SAT-PP on a GeoEye stereomodel (with 50 cm GSD) acquired in 2010; and this has 1 grid resolution and 1 x 1 km dimension, with a total of 965,889 points; and, 3) DSM also derived from photogrammetric procedures using MicMac on a set of airborne images (with 12 cm GSD) acquired in 2009 with 50 cm grid resolution and 1 x 1 km dimension and has a total of 4,564,833 points. All DSMs were delivered in ASCII format.

A cadastral map with 393 buildings, represented as polygons, in shapefile format, and an orthophoto in Tagged Image File Format (tiff), covering an area of 39,513,600 m<sup>2</sup> over the municipality of Trento, were also provided by FBK-3DOM. All datasets were in the WGS84 and map projection UTM32 reference system. A complete list of data used in this study is found in Appendix. A.

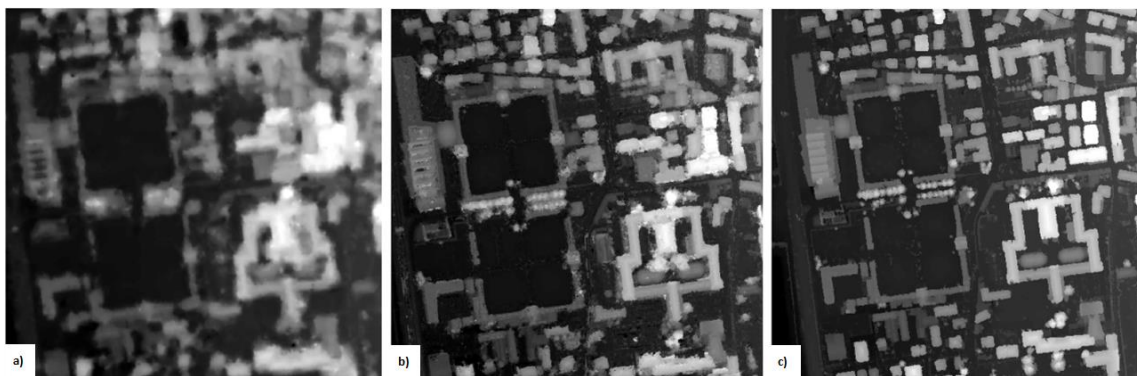
### 3.1. Software

The main software used were ALTPAD, FME, Building Reconstruction and ArcGIS. ALTPAD was used to extract or separate the nDSM and the DTM from the three DSM point clouds. FME 2012 and BREC were employed for generating the 3D model derived from the ALTPAD DSM, in addition to cadastral maps of the zone and orthophoto. FME and BREC 3D models were exported in \*.shp and \*.gml formats. ArcScene was used to visualize the 3D model, as well as extract the height data for later comparisons.

## 4. Methods

### 4.1. Data pre-processing

The dimensions of the DSMs were reduced to make data management easier, and to have quicker calculation time in the software when generating the 3D city model. A mask of approximately 500 x 500 m was created in ArcGIS and all the data were clipped with it. Thus, the final data for this study consisted of three DSMs with the same grid resolution as specified earlier, but having a dimension of 500 x 500 m and reduced numbers of points (see Appendix A, Table 2). The cadastral map was also changed in dimension, like the DSMs, and the number of buildings was reduced to 106, but preserving all the initial attributes. The orthophoto was only changed in its dimension. The final data for the study is presented in Appendix A. The pre-processed DSM data is displayed in Figure 3.



**Figure 3.** DSM from different sensors: a) GeoEye; b) aerial airborne; and, c) LiDAR

### 4.2. Terrain and Buildings extraction in ALDPAT

The digital terrain model and building extraction of the three DSMs were performed with the software ALDPAT, which is designed for removing nDSM and preserving the ground data from LiDAR point clouds (DTM). Several filters are incorporated in it, but the Progressive Morphological filter (PM), which was developed by Zhang, et al. (2003)

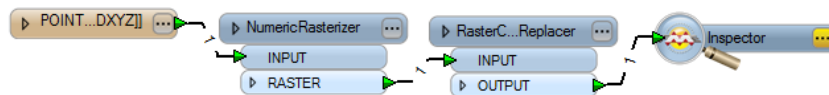
was chosen as it gave the best results in classifying and extracting the terrain and the non-terrain regions. Furthermore, Zhang and Whitman (2005) applied and compared this filter using a DSM derived from LiDAR, while Poli and Caravaggi, (2012) used the same filter with photogrammetric data, obtaining good results.

The parameters used for the PM filter are presented in Figure 4 and were based initially from Zhang, et al. (2003), Zhang and Whitman (2005), and Poli and Caravaggi (2012). The slope, cell size and the initial threshold were the parameters that were changed and tried to obtain the nDSM and DTM. However, the slope was the value that affects the result most because it determines the elevation difference threshold.

Parameter	Value	Type
Cell Size	3.000000	Double
Slope	0.080000	Double
Init Threshold	0.600000	Double
Max Threshold	9999.000000	Double
Window Base	2.000000	Double
Power Increment	1.000000	Double
Window Series Length	8	Integer
Init Radius	1.000000	Double
Window Series	1, 2, 4, 8, 16, 32, 64, 128	Integer
Threshold Series	0.60, 0.84, 1.08, 1.56, 2.52, 4.44, 8...	Double
Result Mode	Terrain	String
Data Mode	Real	String
Min WndSize	1	Integer
Direction	X and Y	String
Rotate Angle	0.000000	Double
Rotate Times	0	Integer

**Figure 4.** Parameters of the Progressive Morphological Filter

In order to compare the results' performance, they were recoded using FME with the transformers *NumericRasterizer* and *RasterCellValueReplacer*. Figure 5 presents the steps using the transformers. Furthermore, maps were created in ArcGIS with the recoded image from FME.



**Figure 5.** Recode flowchart in FME

### 4.3. Building reconstruction in the software FME and BREC

In this section the reconstruction for the 3D model using the software FME and BREC and presented.

#### 4.3.1. Building reconstruction in the software FME

The 3D building in FME will be done in two steps. The first one was the derivation of heights for the 3D buildings, and the second one was the creation of the 3D buildings.

The first step was to create the height of the 3D building. The DSM was filtered in ALDPAT software, and the resulting DTM and nDSM were all imported as point cloud in FME, together with the cadastral building footprints. To generate the height for the LoD1 model, several transformers were applied first in the DTM: 1) *Surfacemodeller* converts the point cloud to raster data; 2) *PointOnRasterValueExtractor* extracts the height values and assigns each of them to polygons; 3) *InsidePointReplacer* replaces the building polygon feature with a center point; 4) *FeatureMerger* merges the value of the center point to each polygon; and, 5) *BoundsExtractor* extracts the maximum and minimum value of each polygon. The whole process ended in a \*.shp file, with height values (Z attribute) and ID for each polygon (Figure 6, top).

The same procedure was used in order to extract the Z value of each polygon with the nDSM (Figure 6, bottom). The \*.shp polygons from the nDSM contained the maximum values, while the \*.shp polygons from the DTM contained the minimum values. ArcMap was used to join the attribute tables of the building polygons, with the minimum and maximum values of the shapefile and to obtain their heights using the following formula.

$$\text{Height of the 3D building} = \text{nDSM} - \text{DTM}$$

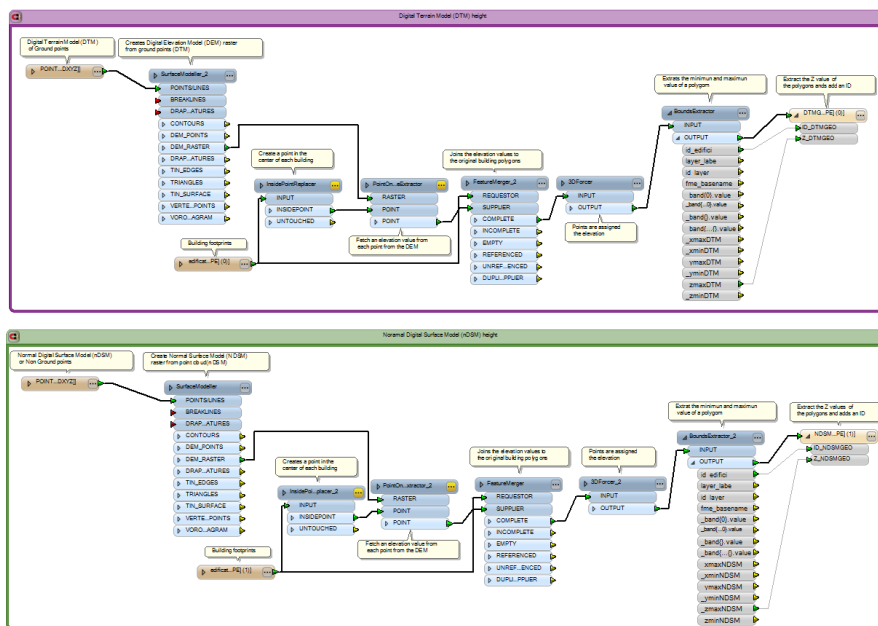
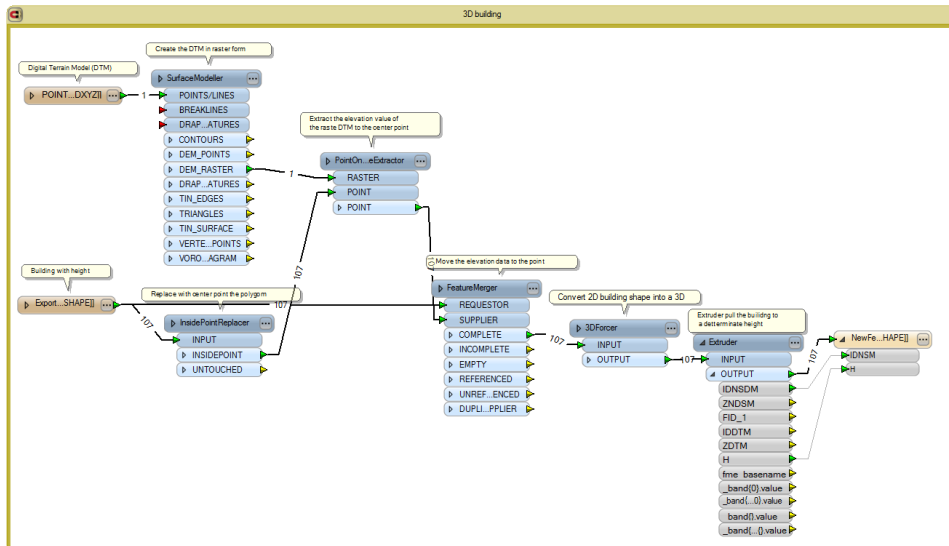


Figure 6. Flowchart for creating the height using the DTM (top) and nDSM (bottom)

The same process is used for all the three data (GeoEye, airborne and LiDAR). The cell size in *surfaced modeller* is substituted without changing the cell spacing in order to have the same grid size. LiDAR and GeoEye cell spacing are 1 x 1m while for Airborne is 50x50 m.

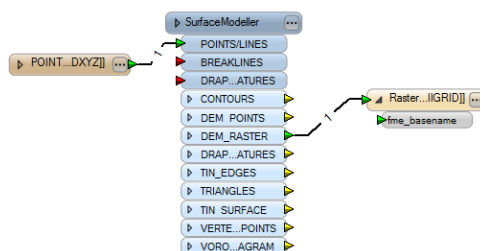
The second step was to create the 3D model, this was done after calculating the height of each polygon, and assigning them as attributes of the building shapefile, the 3D models in LOD1 are generated in FME using several transformers (Figure 7), resulting to different formats such as \*.shp and \*.gml.



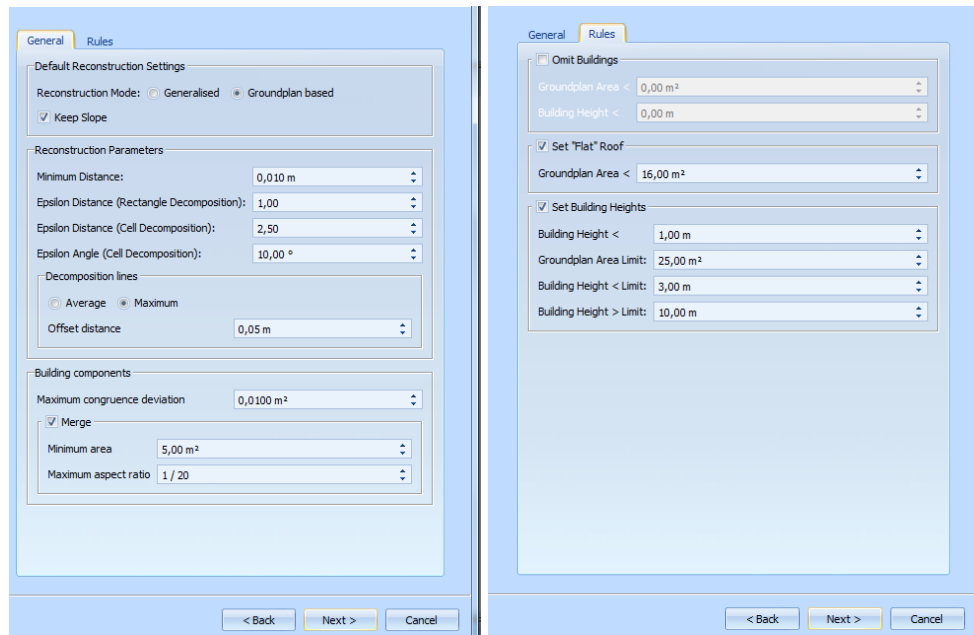
**Figure 7.** Flowchart for creating the 3D buildings in FME

#### 4.3.2. Building reconstruction in the software BREC

The data used for generating 3D models by employing BREC software were cadastral footprints, orthophotos, the DSMs, and the DTMs filtered with ALDTAP and converted using FME to RasterGrid format, using the transformer SurfaceModeller (Figure 8). The LoD1 and LoD2 were generated and exported in \*.shp format and \*.gml format. The same parameters were used in each datasets to see the differences between them. The values of the parameters used were selected based on software recommendation instruction. Although BREC allows manual editing in order to produce an LoD2, this was not used. Figure 9 presents the used parameter.



**Figure 8.** Flowchart for creating raster grid of the DTM and nDSM using FME



**Figure 9.** Parameters used in BREC to reconstruct the 3D buildings

#### 4.4. Methods to analyze the results

In order to evaluate the results, the LiDAR outputs from FME and BREC were used as reference because these software were designed for this kind of data. A qualitative and quantitative comparison of LoD1, and a qualitative comparison of LoD2, as well as their degree of automation and the time of the reconstruction had been effectuated. The software have been compared with each other in a qualitative way with regards to 3D buildings that were derived from LiDAR DSM, with two 3D buildings generated from photogrammetric DSMs (Airborne and GeoEye).

The quantitative analysis of the LoD1 has been examined by manually extracting ten building heights, with the aid of FME. The planimetric coordinates were not studied because these are affected by the footprints from the cadastral map, which was used in all processes; thus the X and Y coordinates did not change their position in the different 3D results. The qualitative analysis of LoD1 and LoD2 was done by placing the 3D buildings against each other. The automation of the software is evaluated as low, medium or high. This was measured by the operator during the reconstruction process. Furthermore, the time of the reconstruction had also been evaluated.

## 4. Results

### 4.1. Feature extraction

The feature extraction affected the 3D buildings directly because these came from the DTM and nDSM. Several interactions, changing the slope parameter, were done in order to obtain the best quality result from different DSM typologies. The interactions to separate the terrain (DTM) from the non-terrain (nDSM), in order to achieve the best result were done by using cadastral footprints and orthophoto. In the Tables 1-3, the

summaries of the parameters adopted in the different tests are reported. The parameter set that provided the best DTM results are underlined in the above mentioned table (slope parameters of 0.5 for LiDAR; 0.35 for Airborne; and, 0.008 for GeoEye), while the results achieved in the test area are illustrated in Figure 10.

**Table 1.** Interaction parameter in order to find the best quality result of LiDAR’s DSM

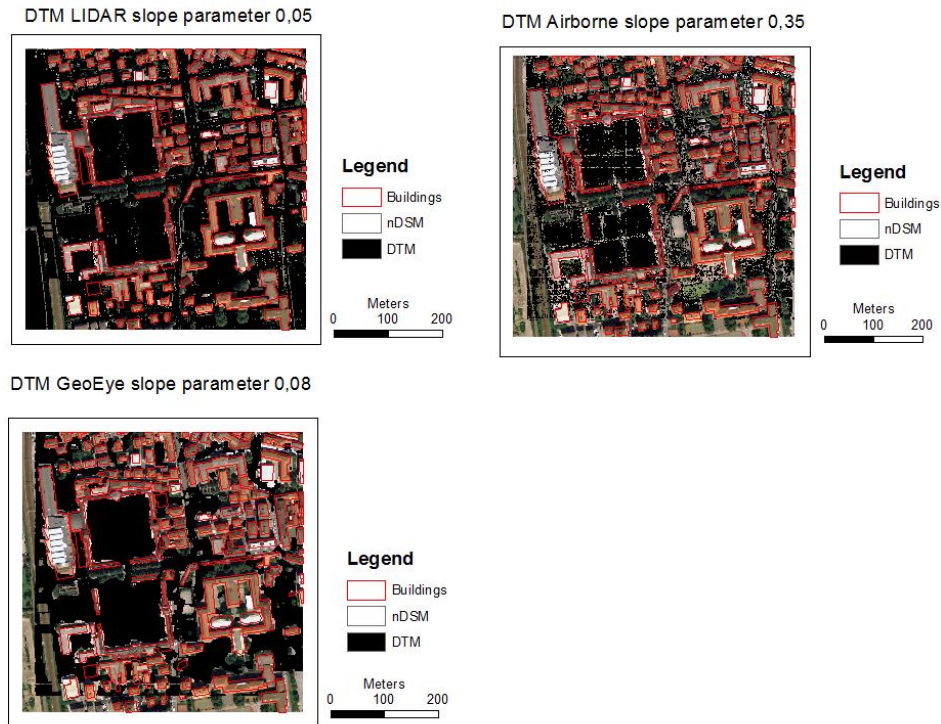
LiDAR’s DSM			
Parameters	Interactions (I)		
	I1	I2	I3
Cell Size	1	1	1
Slope	0.5	0.09	<b>0.05</b>
Ini. Threshold	1	1	1

**Table 2.** Interaction parameter in order to find the best quality result of airborne’s DSM

Airborne’s DSM					
Parameters	Interactions (I)				
	I1	I2	I3	I4	I5
Cell Size	0.5	0.5	0.5	0.5	0.5
Slope	0.08	0.9	0.1	<b>0.35</b>	0.5
Ini. Threshold	0.15	0.15	0.15	0.15	0.15

**Table 3.** Interaction parameter in order to find the best quality result of GeoEye’s DSM

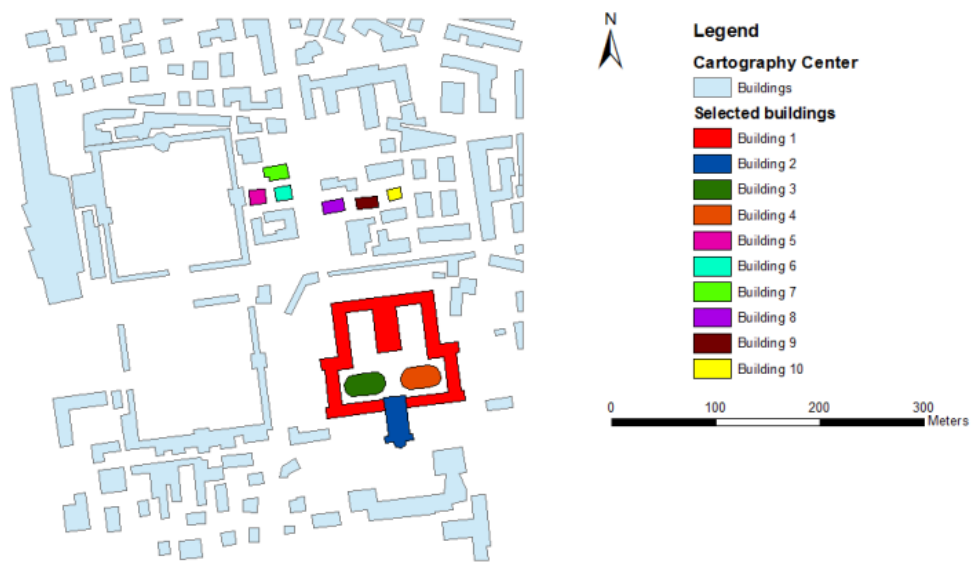
GeoEye’s DSM						
Parameters	Interactions (I)					
	I1	I2	I3	I4	I5	I6
Cell Size	1	1	1	1	1	1
Slope	0.08	0.1	<b>0.008</b>	0.05	0.01	0.8
Ini. Threshold	0.5	0.5	0.5	0.5	0.5	0.5



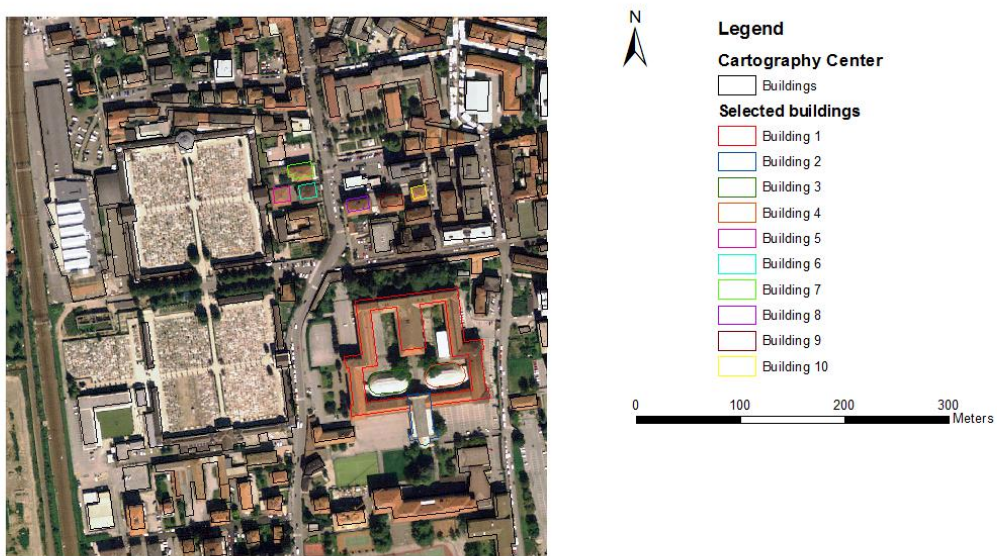
**Figure 10.** Filtered ground map in ALDPAT

#### **4.2. Comparison LiDAR data with the photogrammetric data using BREC and FME**

By separating the terrain (DTM) from the non-terrain (nDSM) in ALDPAT, the 3D models of the study area were created. Among the 3D models in LoD1, ten buildings were selected to be studied in order to compare the quality of the results quantitatively. The buildings that were compared are the most significant of the results output of the 3D model and they are shown in Figure 11 and Figure 12. The buildings in LoD1 and LoD2 were compared qualitatively by visualizing the 3D models' results for the three DSMs (LiDAR, Airborne and GeoEye) that are illustrated in Figures 13 and 14.



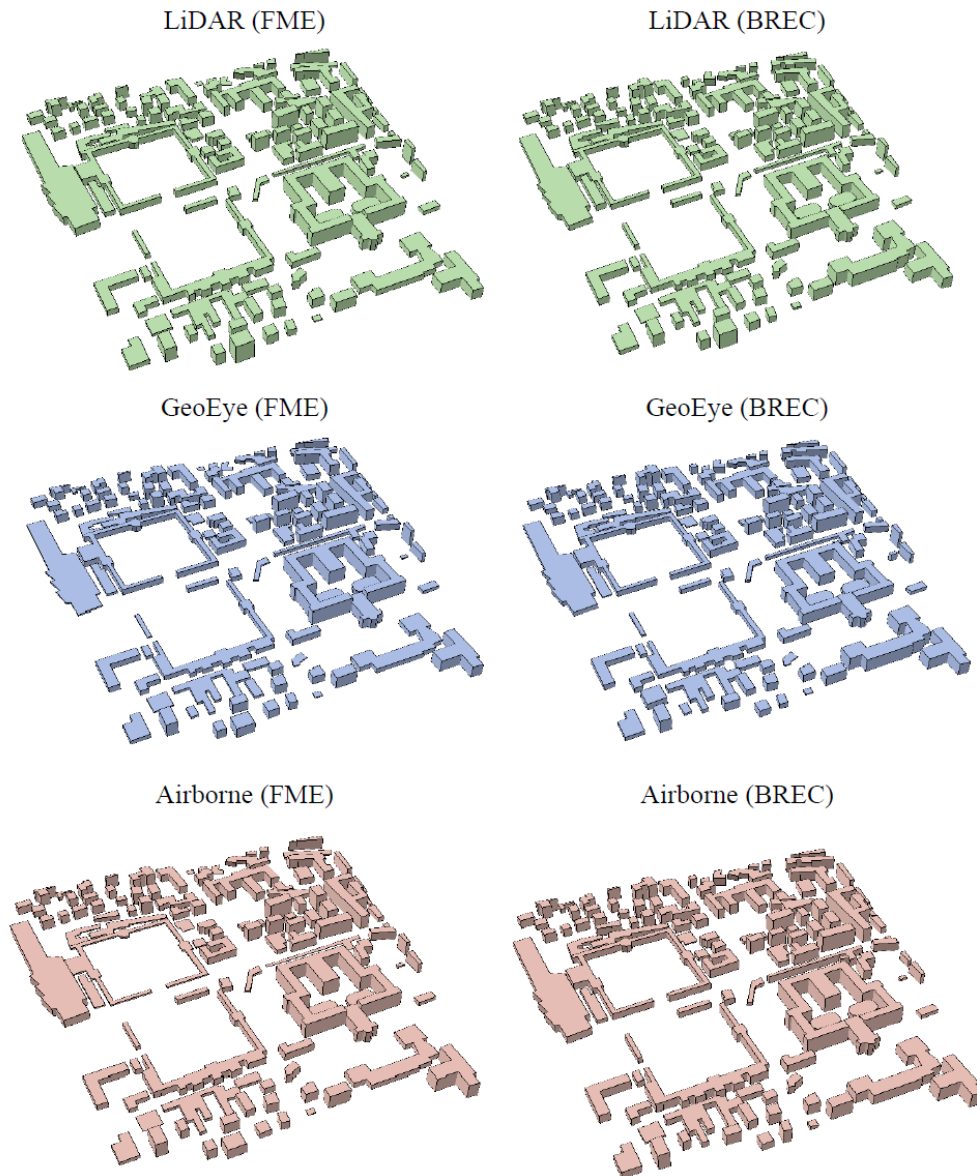
**Figure 11.** Selected building for the quality comparison



**Figure 12.** Selected buildings for the quality comparison with the orthophoto

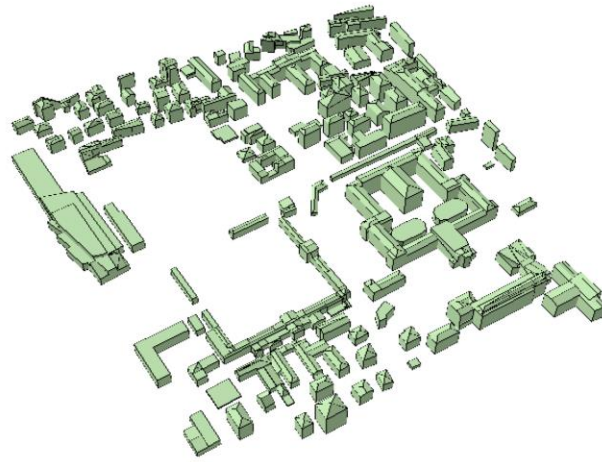
#### 4.2.1. Qualitative comparison of the 3D models

The 3D buildings in LoD1, which are illustrated in Figure 13 that were created with BREC and FME presented similar results qualitatively by doing visual comparison. The said comparison also presented that, with different input data such as LiDAR, GeoEye and Airborne, there were no big differences in LoD1. The 3D buildings in LoD2 of the three DSM imported in BREC presented in Figure 14 were also compared visually. The result showed that they were quite similar. LoD2 was not done in FME software.

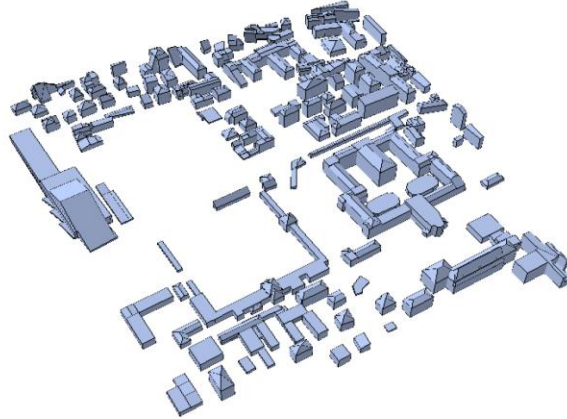


**Figure 13.** Three Dimensional (3D) buildings in LoD1 created by different input data in the software FME and BREC.

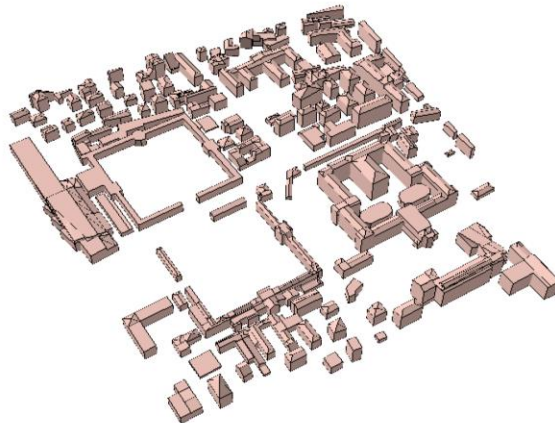
LiDAR (BREC)



GeoEye (BREC)



Airborne (BREC)



**Figure 14.** Three Dimensional (3D) buildings in LoD2, created by different input data in the software BREC.

#### 4.2.2. Quantitative comparison of the 3D models

The quantitative comparison was made for the height of ten selected buildings. Tables 4 - 7 present the value of the buildings and their differences in meters. When the heights of both Airborne and GeoEye data were compared with the reference (LiDAR) data using FME, Building 5 had the largest difference (i.e. 4.62 and 6.74 m, respectively). The smallest difference was in Building 10 of the Airborne data (0.27 m). However, this had not corresponded with the smallest difference result from GeoEye, which was 1.17 m in Building 6, and this was 0.9 m higher than the Airborne data.

**Table 4.** Building height of LiDAR, GeoEye and difference in FME (in meters)

Building	Height (m) LiDAR (FME)	Height (m) GeoEye (FME)	Difference (m)
1	22.14	20.35	1.79
2	16.74	13.89	2.85
3	10.01	7.62	2.39
4	9.60	6.92	2.68
5	8.53	3.91	4.62
6	13.22	12.05	1.17
7	13.26	12.03	1.23
8	21.60	19.67	1.93
9	20.33	18.60	1.73
10	12.52	10.26	2.26

**Table 5.** Building height of LiDAR, Airborne and difference in FME (in meters)

Building	Height (m) LiDAR (FME)	Height (m) Airborne (FME)	Difference (m)
1	22.14	21.44	0.70
2	16.74	16.01	0.73
3	10.01	8.13	1.88
4	9.60	4.31	5.29
5	8.53	1.79	6.74
6	13.22	12.58	0.64
7	13.26	11.35	1.91
8	21.60	19.30	2.30
9	20.33	21.12	0.79
10	12.52	12.25	0.27

Likewise, Airborne and GeoEye data that were compared with the reference (LiDAR) data using BREC, showed high difference values with LiDAR-GeoEye, while the lowest difference was in the LiDAR-Airborne difference (see Tables 6 – 7). Building 4 had the highest difference when LiDAR was compared with GeoEye, while Building 1 obtained the highest difference with Airborne. The smaller difference where in Building 7 and 6 (0.7 and 0.2 m respectively).

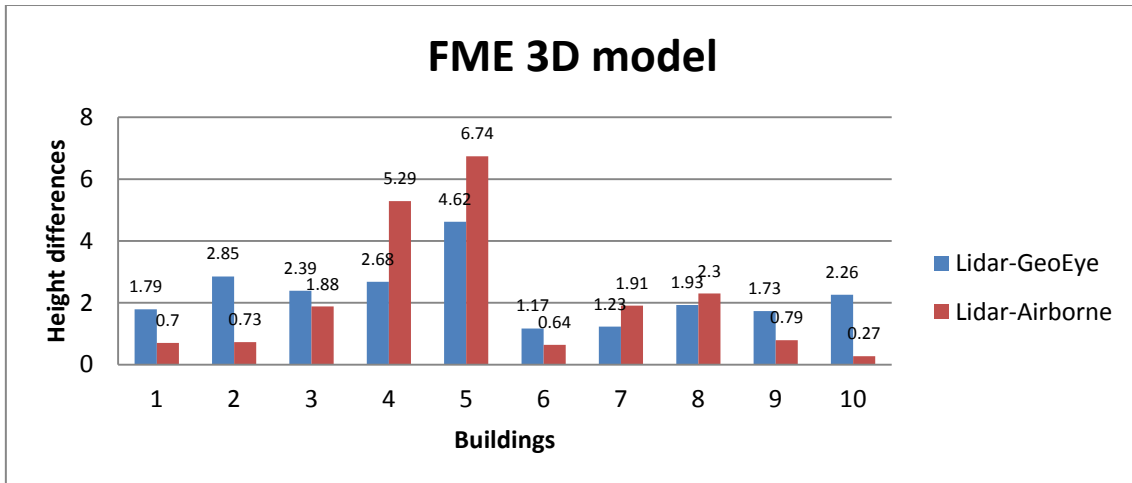
**Table 6.** Building height of LiDAR, GeoEye and difference in BREC in meters

Building	Height (m) LiDAR (BREC)	Height (m) GeoEye (BREC)	Difference (m)
1	18.79	16.71	2.08
2	16.14	15.24	0.90
3	9.41	6.68	2.73
4	9.34	4.84	4.50
5	5.50	4.13	1.37
6	12.40	11.39	1.01
7	13.11	12.41	0.70
8	21.03	18.99	2.04
9	20.50	18.28	2.22
10	12.43	10.06	2.37

**Table 7.** Building height of LiDAR, Airborne and difference in BREC in meters

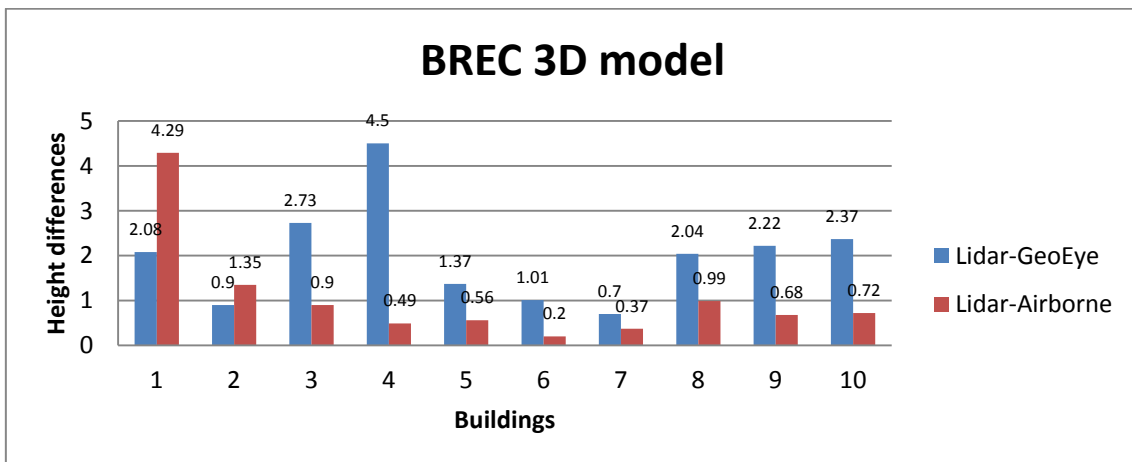
Building	Height (m) LiDAR (BREC)	Height (m) Airborne (BREC)	Difference (m)
1	18.79	23.08	4.29
2	16.14	17.49	1.35
3	9.41	10.31	0.90
4	9.34	9.83	0.49
5	5.50	4.94	0.56
6	12.40	12.20	0.20
7	13.11	12.74	0.37
8	21.03	20.04	0.99
9	20.50	21.18	0.68
10	12.43	13.15	0.72

Figure 15 shows that when using FME and comparing GeoEye with the LiDAR height, the differences between them were huge. However, Building 5 was the one with the highest dissimilarity. By using FME as well, and by comparing Airborne with LiDAR height it was possible to see that the differences between them were low. However, there were two buildings, namely four and five, that exhibit highest height differences. When comparing the difference between LiDAR-GeoEye and LiDAR-Airborne in FME, the highest differences were in Airborne data.



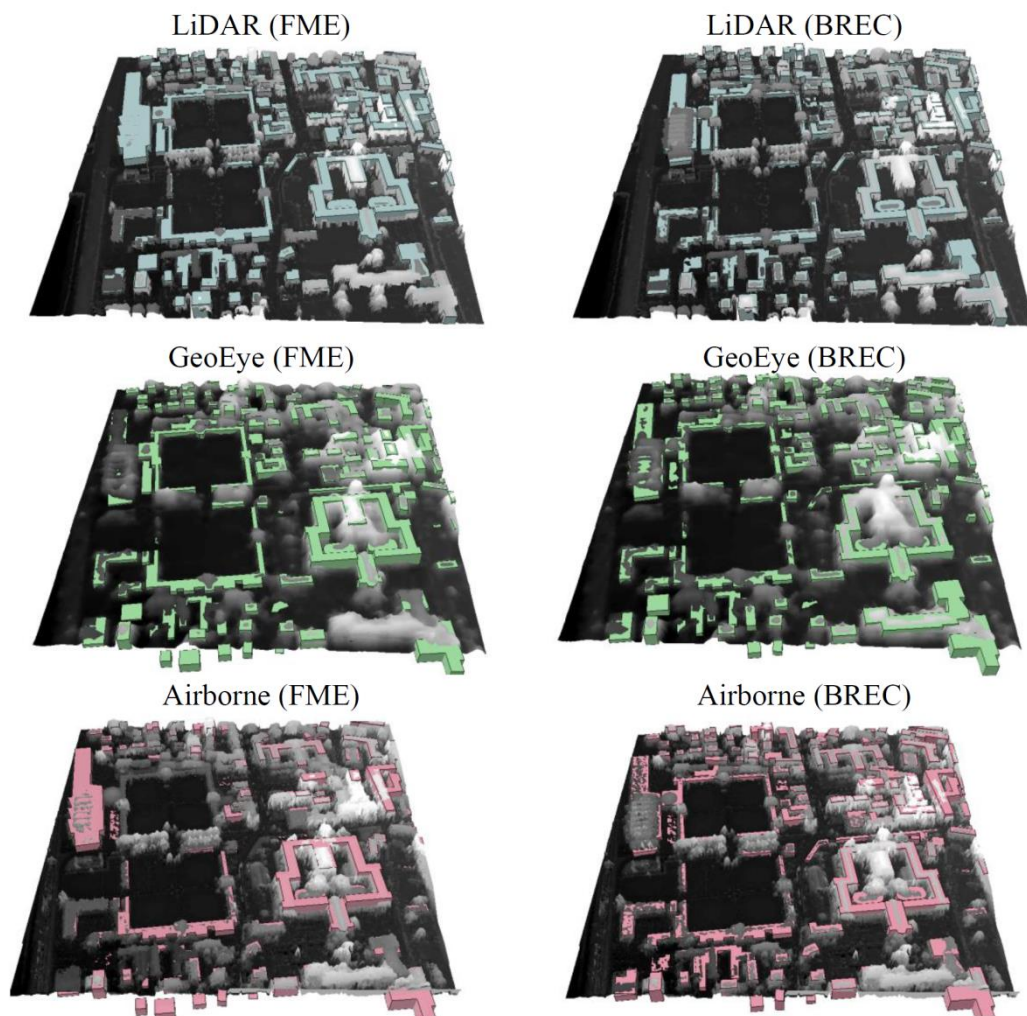
**Figure 15.** Difference in height between Lidar and GeoEye and Lidar and Airborne using the software FME

By using BREC and by comparing GeoEye with the LiDAR height, it is possible to see that most of the differences between them are large (Figure 16). However, Building 4 was the one with the largest difference. By also using and comparing BREC with Airborne and LiDAR data, it was possible to see that the differences between them were low. Nevertheless, Building 1 had the highest difference. When comparing the differences between LiDAR-GeoEye and LiDAR-Airborne in BREC, the highest differences were in GeoEye data, although they were also in Airborne data.



**Figure 16.** Difference in height between LiDAR and GeoEye and Lidar and Airborne using the software BREC

The height differences among the 3D models seemed to stem from the fact that they were in prismatic cube forms, and did not take into consideration the roof of the buildings. Furthermore, the photogrammetric data appeared with noise (such as shadows and occlusions) that could have directly affected the output 3D results. These effects are shown in Figure 17. The high difference in Building 4 can be because of the roof's spherical form, instead of having a square form. This building, as seen in Figure 12, is made of a white material. The differences in Buildings 1 and 2 could have been caused by occlusion and noise in the image matching procedures.



**Figure 17.** 3D buildings created with the software FME and BREC and the DSMs showing how these fit with the 3D buildings.

### 4.3. Comparison of level of automation and the time between FME and BREC

The level of automation was measured during the process of the generation of the 3D city model. This was evaluated according to three different levels: low, medium and high. In this context, the degree of automation in BREC was higher than in FME: This was because BREC did not need the help of the operator in order to create a 3D model in LoD1, while FME required the user in creating the workflow in producing the 3D model.

There are also some problems to highlight. The first one found was that for the DSMs, the image-matching algorithm, to separate ground from non-ground points was not included in both software, thus, needing the ALDPAT software to do the process. Although, FME includes methods to separate them, it is just for LiDAR data.

Another problem was the importation and exportation of the data in both software. BREC needed the input data in a specific format, as opposed to FME that allows importing and exporting different kinds of format, which also makes the visualization of the output easier.

Thus, BREC reconstructed the LoD1 automatically and faster than FME, when using the correct input data format. Furthermore, BREC reconstructed the LoD2 in semi-automatic way because in order to achieve a perfect reconstruction, it needed to be edited with the DSM. The process was also easy.

FME, on the other hand, was slow and it was given the value of medium, as the level of automation. It required experience with the software and familiarity with the transformer to generate buildings in LoD1.

As for the time to reconstruct the 3D buildings, it was evaluated as high, medium and low. Both software, with the data used in this study, reconstructed the 3D buildings in LoD1 in short time so, both had been evaluated as high. Although BREC needed more time to reconstruct LoD2, it was also given the value of high because this done a good approximately reconstruction without manual editing. Table 8 presents the degree of automation of each software and the computational time of the applied methods.

**Table 8.** Degree of automation and reconstructing time for 3D models of the software FME and BREC

Software	Level of automation	Time
FME	Medium	High
BREC	High	High

## 5. Discussion

This section presents a discussion and analysis of the study's findings. First, evaluation of the current state-of-the art 3D city modeling, especially in the commercial software

will be discussed. Secondly, the software automation and computation time will be evaluated. Thirdly, the DSM for LoDs in LiDAR software will also be assessed. Finally recommendations and problems using DSM in LiDAR software will be addressed.

### **5.1. Evaluation of the current state of the 3D city modeling, especially in the commercial software**

The literature review presents different ways to reconstruct 3D city buildings. Most of the studies are done with LiDAR data as input. The 3D buildings, besides using LiDAR data, are combined with other data such as cadastral maps or orthophotos. However, there are also studies with DSMs derived from image matching (Poli, Wolff, & Gruen, 2009; Tack, Buyuksalih, & Goossens, 2012). Since most of the studies are focused on LiDAR DSM, the 3D building reconstruction software available is also focused on LiDAR data as input.

One feature to highlight is the classification of the DSM in the 3D building software. Most of them do not need to perform the data classification when working with LiDAR, as opposed to working with DSMs from image matching. For example, FME, TerraScan and VirtualGrid have their own filter functions to process LiDAR data. However, when the point cloud or DSM is derived from image matching, the data needs to be already classified prior to using that software. In this study, Building Reconstruction (BREC) needed to have the point cloud as already classified even if it is from LiDAR or from DSM derived from image matching. As with FME, although it has filter tools, they are just focused on LiDAR data. Furthermore, both FME and BREC needed cadastral footprints in order to reconstruct 3D buildings.

The different software are also used in several cities in Europe. FME is used in Gävle city, in Sweden (SafeSoftware, 2012b); Building Reconstruction is used to reconstruct the city of Berlin (virtualcitySYSTEMS, 2012); and, TerraScan is used in Spain for creating 3D city models. The main challenge, however, is to generate 3D buildings automatically in a higher level-of-detail. Although this is not yet a reality, in the future, it will be possible to produce an algorithm with the desired automation of the 3D city model (Suveg & Vosselman, 2004).

### **5.2. Comparison of the software automation and computation time**

Building reconstruction (BREC), when compared with FME, could generate LoD1 buildings automatically, and LoD2 semi-automatically. However, this required input to be in the correct format to generate the 3D model. Although it was automatically fast, other software was needed for data conversion. On the other hand, FME did not require the help of any other software because it is a powerful transformer software that can accept any kind of file format. It allows exporting to different kind of format such of \*.dwg, \*.shp, \*.gml, etc. Yet, the process required long time to generate the workflow, and an experienced user was needed to manage the software and the transformers.

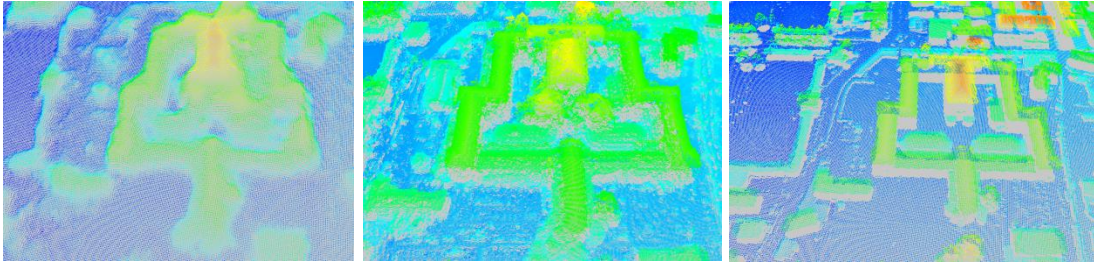
The time of processing for each software depended on the dimension of the input data and the number of points included in it. In this study both software were fast using the same study area dimension.

### **5.3. Comparison of the DSM for LoDs in LiDAR software**

LiDAR data has been used as the primary data by many researchers for reconstructing 3D city models (Forlani, Nardinocchi, Scaioni, & Zingaretti, 2006; Verma, Kumar, & Hsu, 2006), since this provides clear DSM with little noise and other information such as high quality, accuracy density through the use of multi-eco pulses or intensities. For this reason many software have used LiDAR DSM instead of using DSM derived from photogrammetric image matching procedures (SafeSoftware, 2012a; VirtualGrid, 2012; TerraSolid, 2012). However, photogrammetric DSMs, although it is noise-affected, present good results, as shown in several papers. Poli, Wolff, and Gruen (2009) obtained LoD2 with worldwied-1 satellite image and Tack, Buyuksalih, and Goossens (2012) obtained LoD1 with Ikonos satellite image. In these studies, DSMs from satellites images were used and both appeared with noise such as occlusion and shadows (Tack, Buyuksalih, & Goossens, 2012). But even with noise in the photogrammetric DSM, a good LoD1 and LOD2 models were produced. Also, the use of 2D boundary is highly potential to delineate and improve building modeling in DSMs, as Tack, Buyuksalih, and Goossens (2012) point out. In this thesis, the results from the different software and with the different DSM coming from LiDAR, airborne and GeoEye were similar because a cadastral footprint was used to improve the model. Airborne photogrammetric DSM had also less noise and represented the objects better than satellite image, as presented in Figure 18. The typology of the DSM did not affect much the 3D models output results in LoD1, because it just needed some height in order to reconstruct it. However, the typology of the DSM was affected when higher LoDs, such as LoD2, was to be represented.

The software available for 3D city reconstructions use LiDAR data because it defines the objects better. BREC can create LoD1 and LoD2 automatically or semiautomatically. If a satellite image is used to create an LoD2, the reconstruction will not be good enough, as compared with, if LiDAR or Airborne DSM were used, because BREC used manual editing for creating LoD2, and this was based on DSM as a reference.

A good feature of satellite image is that it is possible to obtain a big surface of the terrain using one stereo model, making the reconstruction of the 3D city cheaper. In contrast to this, airborne is expensive due to the need of more time to collect the same data. However, LiDAR is more expensive than photogrammetric data. The DSM of GeoEye, Airbone and LiDAR are presented in Figure 18.



**Figure 18** GeoEye DSM, Airborne DSM and Lidar DSM

#### **5.4. Recommendations and problems using DSM in LiDAR software**

This study presented that it was possible to manage DSM derived from image matching in software focused on LiDAR data. The big problems were found when these DSM were imported in the software FME and BREC in order to reconstruct 3D city buildings in LoD1 and LoD2. However, as it was mentioned in section 4.1, both software (BREC and FME) need to have an algorithm to classify any type of DSM.

In order to reconstruct 3D buildings, cadastral footprints and orthophotos were used. The cadastral footprints were already done and they were not perfect. It is recommended for a perfect reconstruction of the 3D model that the cadastral building footprints are manually done. Otherwise, the 3D model can have some errors. As it is possible to see in Figure 12, the cadastral footprints used in this study did not represent the buildings exactly, therefore, producing an imperfect reconstruction.

### **6. Conclusion and further considerations**

This study examined the different typologies of DSMs such as LiDAR, GeoEye, Airborne in the softwares (FME and BREC) focusing on 3D building models. The results showed that these software could also be used with image matching point clouds after classifying the data e.g. ALTPAD software. A LoD1 model with FME and BREC, and an LoD2 with BREC were obtained in 3D.

In order to automatically create a 3D city model, some problems have to be solved first if the model is reconstructed by using other data beside the DSM point clouds. One of the major problems would be the variation of time of the input data. Normally, the cadastral footprints and orthophotos are not taken at the same time. Thus, the 3D result of the city can be different then the reality. In this thesis, however, there was no such problem because the area of study was a historical site, and this did not change with the time, and all the buildings in the three DSMs of the same study area were presented. This problem can be solved if an orthophoto is used and a cadastral map from the orthophoto is digitized and the DSMs are derived from the image matching. A deeper study must be done in this situation in order to see the result. Another problem is that DSMs created by image matching have shadows and occlusion. This problem can affect directly the DSM quality.

Further research should be performed to compare and validate the 3D buildings from the different software using real height measurement with a total station. Furthermore, due to most of the software use cadastral maps in order to reconstruct 3D building and they are normally in different scale, these should be analyzed studying the influence in the result 3D models. Other LoDs shall also be analyzed qualitatively, as well as by using DSM from image matching.

## References

- Agugiaro, G., Poli, D., & Remondino, F. (2012). Testfield Trento: Geometric evaluation of very high resolution satellite imagery. *Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, (pp. 191-196).
- Axelsson, P. (2000). DEM Generation From Laser Scanner Data Using Adaptive TIN Models. *International Archives of Photogrammetry and Remote Sensing, XXXIII, Part B4*.
- Cai, G., Feng, L., Chen, B., & Lee, T. (2008). Systematic design methodology and construction of UAV helicopters. *Mechatronics*, 18(10), 545-558.
- Chikomo, O. F., Mills, P. J., & Barr, L. S. (2007). *An Integrated Approach to Level-of-Detail Building Extraction and Modelling Using Airborne LIDAR an Optical Imagery* (Vols. XXXVI-3/W49B). Munich, Germany.
- Comune.trento. (2013). *Comune.trento*. Retrieved 04 03, 2013, from <http://www.comune.trento.it/>
- Demoistat. (2013). *Demoistat*. Retrieved 04 05, 2013, from [http://demo.istat.it/bilmens2012gen/index02\\_e.html](http://demo.istat.it/bilmens2012gen/index02_e.html)
- EGN. (2013). *EGN*. Retrieved 04 08, 2013, from <http://www.egm.it/it/trento>
- Festevigiliane. (2013). *Festevigiliane*. Retrieved 04 05, 2013, from <http://www.festevigiliane.it/index.php>
- Festivaleconomia. (2013). *Festivaleconomia*. Retrieved 04 09, 2013, from <http://2013.festivaleconomia.eu/>
- Forlani, G., Nardinocchi, C., Scaioni, M., & Zingaretti, P. (2006). Complete classification of raw LIDAR data and 3D reconstruction. *Pattern Anal Applic*(8), 357-374.
- Haala, N., & Brenner, C. (1999). Extraction of buildings and trees in urban environments. *ISPRS Journal of Photogrammetry & Remote Sensing*, 54, 130-137.
- Hu, J., You, S., & Ulrich, N. (2003). *Approaches to Large-Scale Urban Modeling*. IEEE Computer Society.
- Intergraph Corporation Part of Hexagon Group. (2012). Retrieved 10 25, 2012, from [http://geospatial.intergraph.com/Libraries/Brochures/Stereo\\_Analyst\\_for\\_ERDAS\\_IMAGINE\\_Brochure.sflb.ashx](http://geospatial.intergraph.com/Libraries/Brochures/Stereo_Analyst_for_ERDAS_IMAGINE_Brochure.sflb.ashx)
- Kabolizade, M., Ebadi, H., & Mohammadzadeh, A. (2012). Design and implementation of an algorithm for automatic 3D reconstruction of building models using genetic algorithm. *International Journal of Applied Earth Observation and Geoinformation*, 19, 104-114.
- Kolbe, T., Gröger, G., & Plümer, L. (2005). CityGML-Interoperable Access to 3D City Models. In Z. F. Oosterom, *Geo-information for Disaster Management* (pp. 883-899). New York: Springer.

- Kraus, T., Lehner, M., & Reinartz, P. (2007). Modeling of urban areas from high resolution stereo satellite images. *Proceedings of the ISPRS Hannover Workshop 2007 High-Resolution Earth Imaging for Geospatial Information*.
- Nex, F., & Remondino, F. (2012). Automatic Roof Outlines Reconstruction From Photogrammetric DSM. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 257-262.
- OpenStreetMap. (2012). Retrieved 11 04, 2012, from <http://www.openstreetmap.org/>
- Oude Elberink, S., & Vosselman, G. (2011). Quality analysis on 3D building models reconstructed from airborne laser scanning data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, 157-165.
- Poli, D., & Caravaggi, I. (2012). Digital surface modelling and 3D information extraction from spaceborne very high resolution stereo pairs. *Luxembourg: Publications Office of the European Union*, 1-31.
- Poli, D., Wolff, K., & Gruen, A. (2009). Evaluation of worldview-1 stereo scenes. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVIII-1-4-7/W5 , p.6.
- Remondino, F. (2011). Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. *Remote Sensing*, 3, 1004-1138.
- SafeSoftware. (2012a). Retrieved 11 01, 2012, from <http://cdn.safe.com/resources/fme/FME-Transformer-Reference-Guide.pdf>
- SafeSoftware. (2012b). Retrieved 11 01, 2012, from [http://fmepedia.safe.com/articles/Samples\\_and\\_Demos/City-of-Gavle-in-3D](http://fmepedia.safe.com/articles/Samples_and_Demos/City-of-Gavle-in-3D)
- Sithole, G., & Vosselman, G. (2004). Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point cloud. *ISPRS Journal of Photogrammetry & Remote Sensing*, 59, 85-101.
- Sohn, G., & Dowman, I. (2007). Data fusion of high resolution satellite imagery and LIDAR data for automatic building extraction. *ISPRS Journal of Photogrammetry & Remote Sensing*, 62, 46-63.
- Suveg, I., & Vosselman, G. (2004). Reconstruction of 3D building models from aerial images and maps. *ISPRS Journal of Photogrammetry & Remote Sensing*, 58, 2002-2004.
- Tack, F., Buyuksalih, G., & Goossens, R. (2012). 3D building reconstruction based on given ground plan information and surface models extracted from spaceborne imagery. *ISPRS Journal of Photogrammetry and Remote Sensing*, 67, 52-64.
- TerraSolid. (2012). Retrieved october 15, 2012, from <http://www.terrasolid.fi/en/products/terrascan>

- Trentocultura. (2013). *Trentocultura*. Retrieved 04 09, 2013, from [http://www.trentocultura.it/upload/file/documents/mappa\\_tn09.pdf](http://www.trentocultura.it/upload/file/documents/mappa_tn09.pdf)
- Tuttitalia. (2013). *tuttitalia*. Retrieved 04 08, 2013, from <http://www.tuttitalia.it/trentino-alto-adige/provincia-autonoma-di-trento/88-comuni/altitudine/>
- Vallet, B., Pierrot-Deseilligny, M., Boldo, D., & Brédif, M. (2011). Building footprint database improvement for 3D reconstruction: A split and merge approach and its evaluation. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, 732-742.
- Verma, V., Kumar, R., & Hsu, S. (2006). 3D Building Detection and Modeling from Aerial LIDAR Data. *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*.
- virtualcitySYSTEMS. (2012). Retrieved 11 01, 2012, from <http://www.virtualcitysystems.de/en/2-info.html>
- virtualcitySYSTEMS. (2012). Retrieved 11 02, 2012, from <ftp://ftp.virtualcitysystems.de/>
- VirtualGrid. (2012). Retrieved 10 25, 2012, from <http://www.vrmesh.com/PDFTutorials/VRMeshTutorial-LiDARProcessing.pdf>
- Visittrentino. (2013). *Visittrentino*. Retrieved 04 05, 2013
- Zhang, K., & Whitman, D. (2005). Comparison of Three Algorithms for Filtering Airborne Lidar Data. *Photogrammetry Engineering & Remote Sensing*, 71(3), 313-324.
- Zhang, K., Chen, S.-C., Whitman, D., Shyu, M., Yan, J., & Zhang, C. (2003). A Progressive Morphological Filter for Removing Nonground Measurements From Airborne LIDAR Data. *IEEE Transactions on Geoscience and Remote Sensing*, 41(4), 872-882.

## Appendix A

### Different data sources used in this study

This Appendix presents all data used for the thesis with their characteristics. Table 1 contains the information of the data provided by FBK without changes while Table 2 contains the information of the data reduced to a dimension of 500 X 500 m for determinate the area of study in this thesis.

**Table 1.** Dataset derived from FBK

Data	LiDAR DSM	GeoEye DSM	Airborne DSM	Cadastral map	Ortophoto
Grid resolution	1m	1m	50cm	-	-
GSD	-	50cm	15cm	-	-
Dimensions	Tiles	1x1km	1x1km	-	-
No. of points	-	965 889	456 4833	-	-
Year	-	2010	2009	-	-
No. of buildings	-	-	-	393	-
Reference System	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32
Artibutes	-	-	-	-FID -Shape -id_edificio	-
Area	-	-	-	-	39,513,600 m <sup>2</sup>
Format	ASCII	ASCII	ASCII	Shape file	tiff

**Table 2.** Data created for the study

Data	LiDAR	GeoEye	Airborne	Cadastral map	Ortophoto
Grid resolution	1m	1m	50cm	-	-
GSD	-	50cm	15cm	-	-
Dimensions	500x500m	500x500m	500x500m	500x500m	500x500m
No. of points	270400	244021	1140057	-	-
Year	-	2010	2009	-	-
No. of buildings	-	-	-	106	-
Reference System	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32	WGS84 UTM32
Artibutes	-	-	-	-FID -Shape -id_edificio	-
Area	-	-	-	-	250,000 m <sup>2</sup>
Format	ASCII	ASCII	ASCII	Shape file	tiff

## Appendix B

Flow chart for generating the 3D buildings

