GIMA

Geographical Information Management and Applications

Using airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping

A research for the benefit of land administration in developing countries

MSc thesis final version (27-02-2015)

Student: Niels van Beek

Supervisors: Ir. Edward Verbree (TU Delft)

Dr. ir. Chrit Lemmen (Kadaster)

Professor: Prof. dr. ir. Peter van Oosterom (TU Delft)

Universiteit Utrecht

TU Delft

University of Twente.

Wageningen UR

kadaster

Using airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping

A research for the benefit of land administration in developing countries

Author MSc thesis:

Niels van Beek

Date:

27th of February, 2015

PREFACE

Land administration for developing countries, an important subject which should receive more attention! Why? Because a proper land administration is the backbone of a society. Without a proper land administration, it is hard for developing countries to develop themselves. The past six months, I have enjoyed working on a method to develop a cadastral map, the core ingredient of land administration, from airborne laser scanning data. Considering my background in Human Geography and Planning and Geo-information, it is no surprise that the subject of this MSc thesis has my full attention. My hope is that this MSc thesis will contribute to a better land administration in developing countries, even if it is just a small contribution.

This MSc thesis is performed at the Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster) and is written as part of the Master of Science programme Geographical Information Management and Applications (GIMA). I want to thank Christiaan Lemmen, my supervisor at Kadaster, for sharing his knowledge on land administration in developing countries. Christiaan's enthusiasm and passion for land administration in developing countries is contagious. Edward Verbree and Peter van Oosterom, my supervisors from GIMA, are two other persons I would like to thank. I would like to thank them for their constructive feedback and helping me to guide to the process of conducting a research. In addition, I would like to thank Martijn Rijsdijk and Meindert Sterenberg of Kadaster. They gave me the opportunity to perform my research at Kadaster and let me be part of a great organisation.

Niels van Beek

SUMMARY

Nowadays, 75 percent of the world population does not have access to formal land administration systems, which are able to register and safeguard their land rights. Many people, who do not have access to such systems, are poor and vulnerable. There is an urgent need for sustainable and affordable systems, which are able to secure land rights for all people, in all places, at all time. The cadastral map, which shows land parcels and their boundaries, is one of the most important components of land administration. This research is proposing to construct a cadastral map, according to the general boundary concept, with the use of airborne laser scanning. The goal of this MSc thesis is to investigate the following research question: to what extent is airborne laser scanning suitable for deriving topographic features for the purpose of general boundary based cadastral mapping?

Nowadays, sustainable development has emerged as the major driver for land administration. The cadastre has developed itself towards a multipurpose cadastre, which means that it supports the land administration functions of land tenure, value, use and development (Enemark, 2005). The role of the cadastral map, which requires a large scale, is to show the boundaries of land parcels. The land rights of people can be linked to the land parcels identified on the cadastral map. The construction of a cadastral map in developing countries, could be performed according to the general boundary concept. This approach is, as a first step in development of a cadastral map, more efficient than traditional land surveys. General boundaries coincide with topographic features. Airborne laser scanning can be used to derive this topographic features. Airborne laser scanning is capable of producing highly accurate x,y,z measurements in the form of a three-dimensional point could dataset. The point clouds produced by airborne laser scanning can be considered as highly detailed digital elevations models (DEMs) which matches the earth's surface. Topographic features, which are visible due to height differences, can be detected in these point clouds. It should be noticed, that one of the major advantages of the use of airborne laser scanning is canopy penetration.

It is necessary to know for which particular topographic features to search for in a point cloud. Therefore, an overlay of the Dutch key registry for large scale topography (BGT – Dutch: Basisregistratie Grootschalige Topografie) with the Dutch cadastral map for a selected research area is performed. It is examined that, within the research area, 90 percent of the cadastral boundaries coincides with a topographic feature. The cadastral boundaries do most often coincide with water sections, road sections and delimitations of courtyards. Subsequently, the Nyquist-Shannon sampling theorem is used to theoretically define the most suitable point cloud density for deriving topographic features (which may serve as general boundary). The smallest dimension (i.e. width, length or height) of a topographic object will determine whether a topographic object will be visible in a point cloud or not. Water sections, which appear as a set of points which together form a "line", will for example be harder to detect than a building, which appears as a set of points which together form a "plane".

A workflow for constructing a cadastral map with general boundaries with the use of airborne laser scanning data is created, in order to investigate the suitability of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping. The workflow is implemented for a selected research area. Two-and-half dimensional (2.5D) DEM images are constructed from different point clouds. 2.5D DEM images are created, by overlaying a DEM image of actual values of a point cloud with a hillside shaded DEM image. These images are constructed for the detection of topographic features. After the creation of the 2.5D DEM images, they should to be taken into the field for recordation. Boundaries of parcels can be drawn with a pencil on these 2.5D DEM images. However, this research will not deal with recordation in the field, but will use simulated data. The 2.5D DEM images and the 2.5D DEM images with drawn boundaries (simulated data) are used to construct parcels in a GIS environment. Subsequently, these parcels are overlaid with the 2.5D DEM images and together they form the spatial framework for the cadastral map.

This MSc thesis has demonstrated that airborne laser scanning is suitable for deriving a large share of topographic features, which may serve as general boundary. Topographic features can be detected and extracted from airborne laser scanning data. However, it is necessary to know on forehand, which topographic features in a particular area of country are general boundaries. If this is known, the required point cloud density and the type of analysis can be determined. Topographic features with a small width, length or height require a higher point cloud density to be detected and extracted, than topographic features with a larger width, length or height. In order to make the developed workflow for constructing a cadastral map with general boundaries more valid, the workflow should be implemented in a real case and in different types of areas (for example urban areas and forested areas).

Table of contents

List of figures

List of tables

LIST OF ACRONYMS

2D	Two-dimensional
2.5D	Two-and-half dimensional
3D	Three-dimensional
AHN 2	Height model of the Netherlands (Dutch: Actueel Hoogtebestand Nederlands), second version
AOI	Area of interest
BGT	Dutch key registry for large scale topography (Dutch: Basisregistratie Grootschalige Topografie)
DEM	Digital elevation model
DGPS	Differential global positioning system
DSM	Digital surface model
DTM	Digital terrain model
EDM	Electronic distance measurement
FIG	International Federation of Surveyors
GIS	Geographic information system
GNSS	Global navigation satellite systems
GPS	Global positioning system
IMU	Inertial measurement unit
ISO	International Organization for Standardization
LADM	Land Administration Domain Model
LiDAR	Light detection and ranging
PDOK	Public services on the map (Dutch: Publieke dienstverlening op de kaart)
STDM	Social Tenure Domain Model
TIN	Triangulated irregular network
WMS	Web mapping service

1 INTRODUCTION

This introduction will start with a motivation and background (paragraph 1.1). Subsequently, the problem description (paragraph 1.2) will be discussed. The motivation, background and problem description are explaining why this research is performed. Hereafter, issues which have been researched are identified. These issues are presented by defining research objectives and questions (paragraph 1.3), and research limitations (paragraph 1.4). The methodology describes how this research (paragraph 1.5) is executed. Subsequently, the research area, which is used for achieving the objectives and tackling the research questions and for assessing the obtain results, will be defined (paragraph 1.6). Finally, a reading guide (paragraph 1.7) is provided, to guide the reader through this MSc thesis.

1.1 MOTIVATION AND BACKGROUND

Nowadays, 75 percent of the world population does not have access to formal land administration systems, which are able to register and safeguard their land rights. Most of the people, who do not have access to formal land administration systems, are poor and vulnerable (Enemark et al., 2014). When data about the "people-to-land relationships" is present, it is often incomplete, of low quality and not up-to-date. This applies for both analogue datasets and computerised datasets. The absence of such systems hampers the sustainable development of a developing country. Moreover, it is not beneficial for good governance. Concrete examples of consequences of a lack of a well-managed land administration are land grabbing, land disputes and neglecting of rights of local people. The pressure on land is higher than ever before, due to a growing world population (Lemmen, 2012).

Figure 1: During the G8 summit of 2013, Oxfam draws attention for the problem of unjust land deals by means of posters. Oxfam asked users of social media to share these posters, to disclose this issue to a wider audience

Source: Oxfam, 2014

In the recent years, developing countries are dealing with a commercial pressure on land. Foreign companies or governments are leasing or buying land in developing countries, completely neglecting the local population that uses the land to make a living. The land is used by the foreign investors for food production, biofuel production, tourism developments and natural resources annexation (Hall, 2011). Within the global political circles, land grabbing, land disputes and neglecting of rights of local people are recognised as serious land issues. During the G8 and G20 meetings in 2013, land was an important topic on the agenda (Oxfam, 2014). During these meetings, several organisations (for example Oxfam) tried to raise awareness for land issues, such as land grabbing, among the population of developed countries (see figure 1).

There is an urgent need for sustainable and affordable land administration systems, which are able to secure land rights for all people, in all places, at all time. By securing land rights, a contribution to a sustainable development and a good governance in developing countries will be provided and consequences such as land disputes and land grabbing will be overcome. The International Federation of Surveyors (FIG), in cooperation with the World Bank, have developed a fit-for-purpose land administration approach. The fit-for-purpose land administration approach indicates that "*land administration – and especially the underlying spatial framework of large scale mapping – should be designed for the purpose of managing current land issues within a specific country or region*" (Enemark et al., 2014). The underlying spatial framework of large scale mapping, as mentioned in the quote, is usually a large scale cadastral map which shows the way land is divided in land parcels (Enemark et al., 2014).

According to the fit-for-purpose land administration approach, the use of traditional, high accuracy, expensive land surveying techniques to record land rights are the key bottleneck in current land administration services. The polar method and the Global Navigation Satellite System (GNSS) are the most commonly used land surveying techniques. The polar method (compass, tapes, theodolites, electronic distance measurement (EDM), total station etcetera) effectively measures a bearing and distance from one point to another (Williamson et al., 2010). GNSS can, in combination with a GNSS infrastructure, directly measure the coordinates of land parcel boundaries in a national geodetic reference system with centimetre accuracy (Lemmens, 2011). These land surveying techniques are compatible with the fixed boundary concept. A fixed boundary, is a boundary where the precise line of the boundary is determined by legal surveys and expressed mathematically by distances and bearings, or by coordinates (Williamson et al., 2010). All parties involved in determining the boundary, have to fully agree on the exact position of each boundary point. When there is agreement between parties on the position of the boundary, the position can be marked on the ground with the use of monuments, such as iron pipes. The adjudication, demarcation, survey and registration of fixed boundaries require a lot of time and effort. Sometimes, it takes a few days to complete the registration of one land parcel. The establishment of a cadastral map with fixed boundaries for a country with millions of parcels will last many years, or in some cases even decades and centuries. Besides time and effort, an enormous amount of money is necessary, as well as legal and technical expertise (Bogaerts & Zevenbergen, 2001). As mentioned before, many developing countries have an urgent need for a land administration system. Therefore, the construction of a cadastral map according to the fixed boundary concept by using traditional, high accuracy, expensive land surveying techniques is not really suitable for this need of developing countries.

Because developing countries have an urgent need for a land administration systems, the fit-for-purpose land administration approach proposes the use of imagery (aerial or satellite) as land surveying technique and the use of the general boundary concept to determine boundaries of land parcels. Concerning the general boundary concept, the emphasis is on the visible features in the field. In general, it is supposed that the visible features in the field coincide with the (approximate) position of the boundary (Bogaerts & Zevenbergen, 2001). The visible features in the field can be mapped relatively easily in an automated manner; a map with the graphical representation of the boundaries can be constructed. When these visible features in the field are displayed on a map, they are called topographic features. However, the exact location of the legal boundaries is not indicated by general boundaries, although they are clearly visible in the field in the form of visible features (ditches, hedges, walls etcetera) (Bogaerts & Zevenbergen, 2001). Photogrammetry is compatible with the general boundary approach. Photogrammetry can be used to produce aerial imagery. Subsequently, aerial imagery is used to identify topographic features (such as ditches, roads, houses etcetera), which either represent a boundary or are related to a boundary (Williamson et al., 2010). The general boundary concept can be used for building cadastral maps of areas, where topographic features are present.

1.2 PROBLEM DESCRIPTION

However, using photogrammetry as land surveying technique, as the fit-for-purpose land administration approach proposes, has its disadvantages. Particular weather conditions, such as haze, clouds and winds, negatively affect the aerial imagery. Because of these particular weather conditions, the number of suitable days for photogrammetric surveys is limited. Another disadvantage is, that particular topographic features which could serve as general boundary may not be detected on aerial imagery, due to tree canopy, dense vegetation or rough terrain with sharp slopes. Beside photogrammetry, airborne laser scanning may be a surveying technique, which is suitable for detecting topographic features for the purpose of general boundary based cadastral mapping. Airborne laser scanning, or airborne light detection and ranging (LiDAR), is a remote sensing technique, which is without doubt one of the most successful data acquisition techniques introduced in the last century (Lemmens, 2011). The disadvantages of photogrammetry can be undone by airborne laser scanning. Airborne laser scanning is an active remote sensing technology, which means that the laser scanner generates itself the radiation it senses. Airborne laser scanning uses a laser light, to produce highly accurate x,y,z measurements in the form of a 3D point cloud dataset (Huurneman et al., 2009). One of the advantages of airborne laser scanning is, that it has the capacity to partially penetrate through vegetation. Topographic features, which could serve as general boundaries and are hidden underneath a forest roof, can be mapped with the use airborne laser scanning. In addition airborne laser scanning provides a better accuracy of height data (due to the z-coordinate) than photogrammetry. This is not only important for 3D applications, but also for the identification and mapping of topographic features, which are characterised by height differences. For example:

ditches which are dry may not be recognised on aerial imagery, because they appear the same as land. With the use of airborne laser scanning, such topographic features can be recognised due to height differences (Waterschapshuis, 2012).

Figure 2: A hillside shaded DEM image of the rural area of Barneveld, constructed from airborne laser scanning data

Source: OpenTopo, 2014

The contents of figure 2 confirms that topographic features can be derived from airborne laser scanning data. The figure shows a hillside shaded DEM image of the rural area of Barneveld (The Netherlands), derived from airborne laser scanning data (AHN 2). Hillside shaded DEM images are created by simulating the sun's effect on height and depths within a landscape. A hillside shaded DEM image is very useful for the visualisation of local height variations (Maas & Vosselman, 2010). This figure is showing the relation between the differences in height (relief) in the terrain and detecting topographic features, which may serve as general boundary. Several ''lines" can be detected. These lines are representing elevations and depths (height differences) in the terrain. Elevations are for example hedges. Depths are for example ditches. In other words: it is possible to detect topographic features, which may serve as general boundary, with the use of airborne laser scanning.

Using airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping, receives little scientific attention. Therefore, there is not much knowledge about this theme. The problem this research addresses, is deriving topographic features from airborne laser scanning data for the purpose of general boundary based cadastral mapping. According to the general boundary concept, a general boundary coincides with a topographic feature. The topographic features may be detected from airborne laser scanning data and used to determine the boundaries of land parcels. Subsequently, land rights and land uses can be linked to the land parcel. In this way, land parcels are identified and land rights and land uses can be registered.

1.3 Research objectives and questions

The goal of this research is to investigate the suitability of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping. In order to achieve this goal, the following research question is defined: To what extent is airborne laser scanning suitable for deriving topographic features for the purpose of general boundary based cadastral mapping? The research goal and the research question are devised for the benefit of countries, which have an urgent need for a cadastral map. Land administration systems need (in principle) a cadastral map to operate. Therefore, building a cadastral map will contribute to a sustainable development and a good governance in every country in the world. In order to achieve the research goal and research question, several objectives and corresponding sub question are determined:

Objective 1: Define the role of the cadastre and its cadastral map.
Sub question 1: What is the role of the cadastre and its cadastral map?

This objective and corresponding sub question will discuss the role of the cadastre and its cadastral map. Different components of land administration will be intensively discussed: the land management paradigm, land administration systems and finally the cadastre and its cadastral map.

Objective 2: Identify the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping.
Sub question 2: How can airborne laser scanning be beneficial for deriving topographic features for the purpose of general boundary based cadastral mapping?

In order to identify and understand the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping, an explanation will be provided on the principle of airborne laser scanning and its advantages. Subsequently, it will be discussed how the advantages of airborne laser scanning can be used for general boundary based cadastral mapping. In this way, the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping will be clear, although the problem description already paid little attention to the benefits of airborne laser scanning for general boundary based cadastral mapping.

Objective 3: Examine how often existing cadastral boundaries coincide with particular topographic features.
Sub question 3: To what extent do existing cadastral boundaries coincide with particular topographic features?

One topographic feature will more often serve as general boundary than another topographic feature. A ditch for example, is more likely a possible boundary than a granary. By examining the coincidence of existing cadastral boundaries with particular topographic features, an indication can be provided on which particular topographic feature often coincides with an existing cadastral boundary. When this is known, priority can be given to search in a point cloud for particular topographic features with a high probability of being a cadastral boundary. Moreover, when existing cadastral boundaries do often coincide with particular topographic features, then there is a good reason to further investigate how to derive topographic features from airborne laser scanning data for the purpose of general boundary based cadastral mapping. It should be noticed that cadastral boundaries coincide with different types of topographic features, depending on the type of area. For example: in urban areas, cadastral boundaries will coincide with other topographic features than in rural areas.

Objective 4: Provide a recommendation on the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping.
Sub question 4: Which point cloud density is suitable for deriving topographic features for the purpose of general boundary based cadastral mapping?

When a (developing) country wants to order an airborne laser scanning survey for the purpose of general boundary based cadastral mapping, it is necessary to define the most suitable point cloud density. The smallest point cloud density will be the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping, because the price of airborne laser scanning surveys increases when the point cloud density becomes higher. In addition, when a point cloud has a high density, a lot of points have to be processed. This is very costly and time-consuming.

Objective 5: Design a workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from of airborne laser scanning data.
Sub question 5: How to construct a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data?

This objective and corresponding sub question will deal with identifying methods and techniques for (1) detecting and extracting topographic features from 2.5D DEM images, (2) recordation in the field, (3) constructing parcels in a GIS environment and (4) constructing a spatial framework for a cadastral map.

Objective 6: Propose a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data.

Sub question 6: How does a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data appear?

After developing the workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning, the workflow will be implemented and tested for an airborne laser scanning dataset.

1.4 Research limitations

Although the research scope is indicated by the research objectives and the research questions, this paragraph tries to further delimit the research by discussing some research limitations (i.e. aspects and issues which are out of scope for this research). Below, some of the research limitations are listed:

- The exact cost aspect of airborne laser scanning is out of scope.

The exact cost aspect of airborne laser scanning is not part of this research, because it would take too much time to figure out the cost of acquiring airborne laser scanning data and using software packages which are able to process airborne laser scanning data. However, the cost aspect is not completely out of scope. Sub question 4 will discuss the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping. It is obvious that using a smaller point cloud density for general boundary based cadastral mapping is cheaper than using a higher point cloud density.

- Other forms of laser scanning (for example mobile laser scanning and terrestrial laser scanning) are out of scope.

This research will design a workflow for constructing a cadastral map with general boundaries with the use topographic features derived from airborne laser scanning data. Constructing a cadastral map with general boundaries with the use of other forms of laser scanning is out of scope.

- Geo-referencing of the laser scanning data is out of scope

The developed workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning does not take into account the georeferencing of the data which is acquired with the use of airborne laser scanning. The developed workflow will be implemented by using an airborne laser scanning dataset, which already have been georeferenced.

- Fully automated point cloud processing is out of scope

This research will not deal with fully automated point cloud processing. In order to construct a cadastral map with general boundaries, point clouds are processed stepwise, with human intervention.

- 3D cadastre is out of scope

Although airborne laser scanning produces 3D point clouds, this research will not deal with a 3D cadastre. The 3D cadastre is beneficial for densely built-up areas with large constructions and complex infrastructures, which also are present in developing countries. Densely built-up areas, with large constructions and complex infrastructures, require a proper registration of the legal status. This can be provided to a limited extent by 2D cadastres.

1.5 Methodology

This paragraph will discuss how this research is executed. Each objective and corresponding sub research question, which are defined in the paragraphs above, will be discussed on how they will be achieved.

Objective 1: Define the role of the cadastre and its cadastral map.
Sub question 1: What is the role of the cadastre and its cadastral map?

This objective will be achieved and this sub question will be tackled by preforming a literature review. By preforming a literature review on relevant scientific books and papers concerning land administration, knowledge will be gained on the role of the cadastre and its cadastral map.

Objective 2: Identify the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping.
Sub question 2: How can airborne laser scanning be beneficial for deriving topographic features for the purpose of general boundary based cadastral mapping?

This objective will be achieved and this sub question will be tackled by preforming a literature review. A literature review on relevant scientific papers and books needs to be performed, to gain knowledge about airborne laser scanning. Several scientific papers and books can be used to intensively discuss the principle of airborne laser scanning, the advantages of airborne laser scanning and how the advantages of airborne laser scanning can be used for general boundary based cadastral mapping.

Objective 3: Examine how often existing cadastral boundaries coincide with particular topographic features.
Sub question 3: To what extent do existing cadastral boundaries coincide with particular topographic features?

This objective will be achieved and this sub question will be tackled by analysing an overlay between the BGT and the Dutch cadastral map for a research area, which is defined in paragraph 1.6. The research area is within the Netherlands and is chosen because of data (i.e. a topographic map and a cadastral map) availability. No data of a developing country is available. The overlay will be performed with the use of GIS software. The analyses is performed, by manually counting the cadastral boundaries which are coinciding with particular topographic features. The BGT is obtained through Kadaster, which is the administrator of the BGT. The Dutch cadastral map is obtained with the use of a web mapping service (WMS). The scale range of the BGT is the reason why the BGT is used for the overlay with the Dutch cadastral map. Normally, cadastral maps range from scale of 1:500 to 1:10.000 (Enemark & Williamson, 1996). This is corresponding with the scale range of the BGT. It means that the accuracy of the topographic features of the BGT and the cadastral boundaries are similar.

Objective 4: Provide a recommendation on the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping.
Sub question 4: Which point cloud density is suitable for deriving topographic features for the purpose of general boundary based cadastral mapping?

This objective will be achieved and this sub question will be tackled by defining the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping with the use the Nyquist-Shannon sampling theorem (see paragraph 5.1). Therefore, a literature review on the Nyquist-Shannon sampling theorem needs to be performed. After preforming the literature review, the sampling theory can be tested. The sampling theory will be tested by analysing the visibility of a particular topographic features in point clouds with different densities. The particular topographic features will be chosen within the research area, which is defined in paragraph 1.6. The second height model of the Netherland (AHN 2), which is a point cloud obtained through airborne laser scanning, will be used as test data.

Objective 5: Design a workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data.
Sub question 5: How to construct a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data?

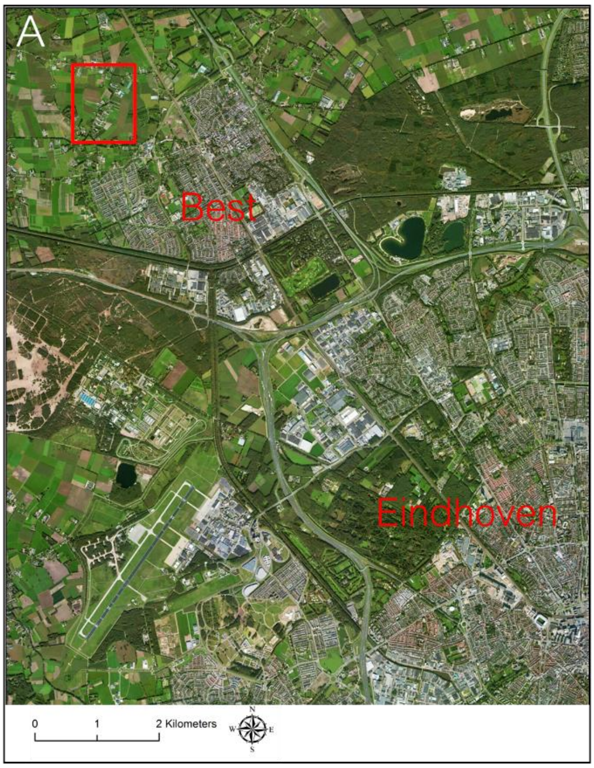
This objective will be achieved and this sub question will be tackled by developing a workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data. This workflow will discuss several methods and techniques, which can be used to construct a cadastral map according to the general boundary concept with the use of airborne laser scanning data. The workflow will consist of four different parts: (1) detecting and extracting topographic features from 2.5D DEM images, (2) recordation in the field, (3) constructing parcels in a GIS environment and (4) constructing a spatial framework for a cadastral map. In the "detecting and extracting topographic features from 2.5D DEM images" part of the workflow, methods and techniques for point cloud filtering, rasterization and topographic feature detection will be discussed. The "recordation in the field" part of the workflow will describe how to record land rights in the field. The “constructing parcels in a GIS environment” part of the workflow will deal with constructing parcels, based on the evidence which is collected in the field. Finally, the “constructing a spatial framework for a cadastral map” part of the workflow will discuss how the construct a cadastral map with general boundaries.

Objective 6: Propose a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data.
Sub question 6: How does a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data appear?

This objective will be achieved and this sub question will be tackled by implementing the workflow, which is developed by answering sub question 5. The workflow will be tested with the use of GIS software for the research area, which is defined in paragraph 1.6. AHN 2 will be used as test data. The “recordation in the field” part of the workflow will not be executed. For this part of the workflow, simulated data will be used.

1.6 RESEARCH AREA

Figure 3: Image A shows the location of the research area (red rectangle) with respect to the city of Eindhoven and the village of Best. Image B shows the research area (a part of the municipality of Best)



The defined research area will be used for 3 purposes:

1. Answering sub question 3: an overlay of the BGT and the Dutch cadastral map will be performed for the research area, to provide an indication on the coinciding of existing cadastral boundaries with particular topographic features.
2. Answering sub question 4: an area of interest (AOI), containing particular topographic features, within the research are will be chosen. Subsequently, the visibility of particular topographic features in point clouds with different densities will be analysed. AHN 2 will be the used test data.
3. Answering sub question 6: the workflow, which is developed during sub question 5, will be implemented with the use of AHN 2 data for the research area.

The research area is a rural area, because the general boundaries concept is suitable for such a type of area. Rural areas have been cultivated for a long time. Land patterns are well established and topographic features are present (Lemmens, 2011). A rural area in the Netherlands will also be chosen as research area, because there is airborne laser scanning data available (AHN 2) for the research area. It would be better to choose a research area in a developing country. However, there is no airborne laser scanning data of an area in a developing country available on the short term. Therefore, the choice is made to choose a research area in the Netherlands and use AHN 2, which is obtained with the use of airborne laser scanning technology. Another reason to choose for this research area, is the availability of the BGT for this particular area. The Dutch cadastral map is available for the whole of the Netherlands and does not influence the choice for this particular research area. The chosen research area is a small area located in the south of the Netherland, near the city of Eindhoven and the village of Best. The research area is part of the municipality of Best (see figure 3) and covers an area of 1,25 square kilometres. It contains many topographic features, which could serve as general boundary.

1.7 Reading guide

After the introduction, chapter 2 will deal with examining the role of the cadastre and its cadastral map. The focus of this research is on constructing a cadastral map with general boundaries. General boundaries coincide with topographic features. Therefore, chapter 3 will examine how airborne laser scanning can be beneficial for deriving topographic features, which can serve as general boundary. Chapter 4 will examine how often cadastral boundaries coincide with particular topographic features in a selected research area. In this way, an indication is available on which particular topographic features will have the highest chance of being a general boundary. Then it will also be known, which particular topographic features to search for in a point cloud. The particular topographic feature type, after which has to be searched for in a point cloud, requires a particular point cloud density. Chapter 5 will deal with defining the most suitable point cloud density for detecting particular topographic features. Chapter 6 will discuss how a cadastral map with general boundaries can be constructed with the use of airborne laser scanning data. This chapter will deal with the development of a workflow for this issue. The workflow for constructing a cadastral map with general boundaries with the use of airborne laser scanning will be implemented for the research area defined in the previous paragraph. The implementation of the workflow will be discussed in chapter 7. Subsequently, a conclusion, discussion and recommendations for future research will be provided.

2 The role of the cadastre and its cadastral map

Because constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data is the main focus of this MSc thesis, it is necessary to know what the role of a cadastral map is. This chapter will examine the role of the cadastre and its cadastral map and thereby objective 1 (define the role of the cadastre and its cadastral map) will be achieved and sub question 1 (what is the role of the cadastre and its cadastral map?) will be tackled. Although the cadastre and its cadastral map are the core ingredients of modern land administration theory, they are recognised as only part of the land management paradigm, which is the cornerstone for modern land administration theory (Williamson et al., 2010). First of all, paragraph 2.1 will discuss the value of land. Paragraph 2.2 will discuss the land management paradigm. Subsequently, paragraph 2.3 will explain a land administration system, the core infrastructure of the land management paradigm. After explaining the land management paradigm and land administration systems, the cadastre will be discussed in paragraph 2.4. Finally, the cadastral map, one of the most important components of a cadastre, will be discussed in paragraph 2.5.

2.1 Value of land

"Land is the ultimate resource, for without life on earth cannot be sustained. Land is both a physical commodity and an abstract concept in that the rights to own or use it are as much a part of the land as the objects rooted in its soil. Good stewardship of the land is essential for present and future generations" (UN-ECE, 1996).

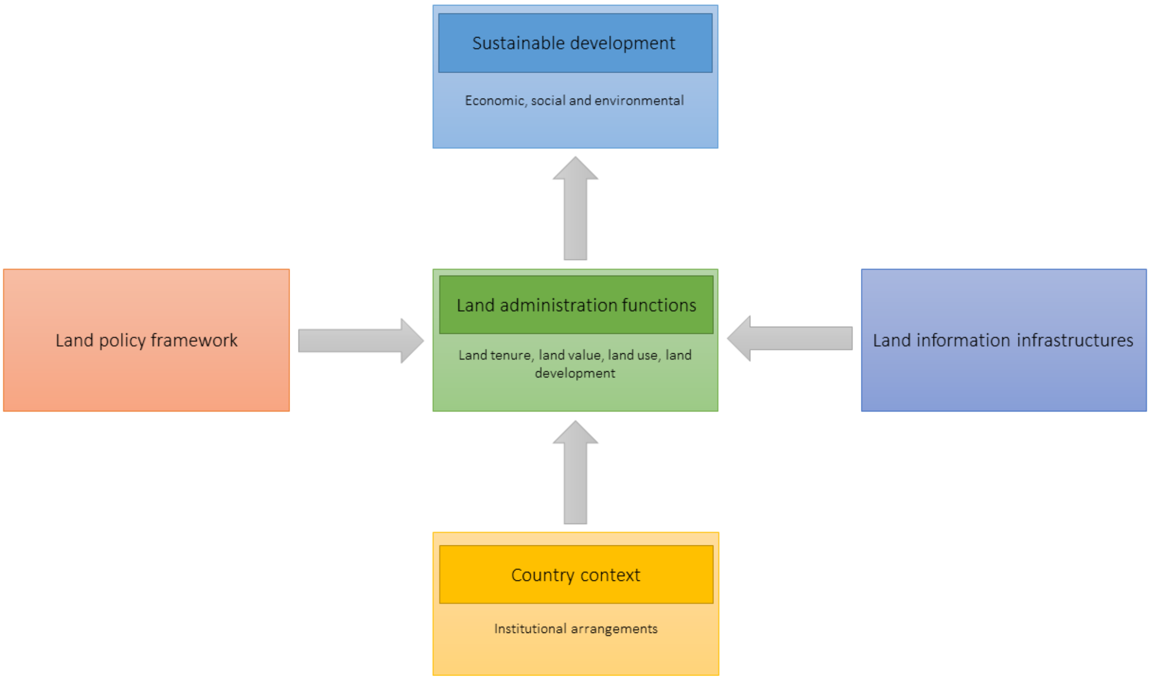
All countries in the world have to deal with the management of land. According to the quote this paragraph started with, land can be considered essential for mankind's being on earth. Henssen (1995) defines land as "*an area of the surface of the earth together with water, soil, rocks, minerals and hydrocarbons beneath or upon it and the air above it. It embraces all things which are related to a fixed area or point of the surface of the earth, including the areas covered by water, including the sea*" (Henssen, 1995). Land is essential in producing food, and therefore directly linked to food security. Land is important in producing raw materials for building shelter and making clothes. It also offers mineral resources, such as oil, ore, black coal and gold. In short, one can say that land provides in the basic needs of humans, eases living circumstances and ascertains well-being (Lemmens, 2011). Besides being essential for our living and well-being, land is for many of us also a source of wealth. Bell (2006) is mentioning that, in general, the major assets in any economy are land and the constructions which are built on this land. In most countries, three-quarters of the nation wealth is accounted by land (Bell, 2006).

The quote is also indicating that a good stewardship of the land is essential for present and future generations. Williamson et al. (2010) are conforming this. They are considering a well-managed land administration essential for a sustainable development in every country in the world. Land administration is concerning "*the processes of determining, recording, and disseminating of information about ownership, value and use of land when* *implementing land management policies*" (Williamson et al., 2010). According to the International Organization for Standardization (ISO), land administration is described as "t*he process of determining, recording and disseminating information about the relationship between people and land*" (ISO 19152, 2012). A well-managed land administration will have a positive impact on economic growth, environmental protection, social justice and equity and political stability. Beside these dimensions of sustainable development, another dimension should be added: governance. Governance refers to the processes of decision making and the processes of implementing these decisions. In other words: governing. Therefore, land administration is essentially about good governing (Williamson et al., 2010).

2.2 The land management paradigm

During the last two decades, sustainable development has emerged as the major driver for land administration. In order to secure land rights for all and support sustainable development and good governance, a modern land administration theory is developed. The land management paradigm (see figure 4) is the foundation of modern land administration theory. Beside sustainable development, globalisation and information technology are two other major drivers for modern land administration. Globalisation is concerning an increasing interconnectedness between societies and jurisdictions. Globalisation is recognised as a new stage in world (land) policy, which will assist in improving the quality of people's lives. This will be achieved by cooperation between different societies and jurisdictions. Information technology, another major driver for land administration, provides the capacity to reorganise land information (Ting & Williamson, 1999).

Figure 4: The land management paradigm



Source: Williamson et al., 2010

Within the land management paradigm, the land administration functions of land tenure, land value, land use and land development are considered holistically. Land management is broader than land administration. As mentioned before, land administration is concerning the processes of determining, recording, and disseminating of information about ownership, value and use of land when implementing land management policies. Land management, on the other hand, covers the process of placing the resources of land into good effect. Land management encloses all the activities concerning the management of land and natural resources, which are necessary to fulfill political objectives and to attain sustainable development (UN-ECE, 1996).

Throughout the world, countries have different organisational structures for land management. These organisation structures reflect the cultural and judicial settings of that particular country. In the course of time, institutional arrangements may change to better support the implementation of land policies and good governance. Within the country context, the paradigm consists of three components which are describing the land management activities: land policy, land information infrastructure and land administration functions. The land administration functions support sustainable development (Williamson et al., 2010).

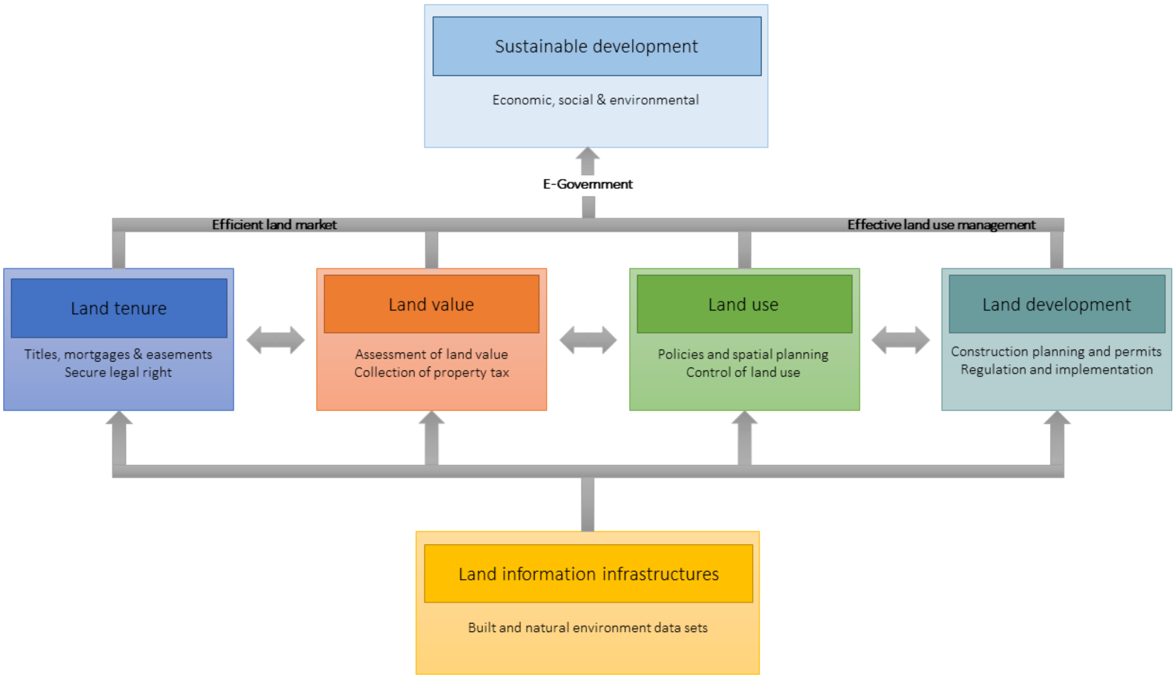
Within the land management paradigm, a country has to deliver its land policy goals. A land policy is part of an overarching national policy on promoting objectives, including sustainable development and good governance. Land policy refers to how governments deal with the management of society's major asset: its land. Land policies may for example concern: security of tenure, land markets, land use planning and control, taxation of land and the management of natural resources.

The range of four land administration functions (land tenure, land value, land use and land development) are the operational component of the land management paradigm. These functions have to ensure a proper management of rights, restrictions, and responsibilities in relation to property, land and natural resources. Land tenure is about securing and transferring rights in land, but also in natural resources. Land value is concerning the valuation and taxation of land and properties. Land use deals with planning and controlling land use and the use of natural resources. Land development is about the planning of infrastructures and constructions and implementing utilities. The land administration functions must interact with each other to deliver overall (land) policy objectives. An appropriate land information infrastructure, which includes cadastral and topographic datasets, is facilitating the four land administration functions (Enemark et al., 2005).

2.3 Land administration systems

A land administration system is an infrastructure, which facilitates the implementation of land policies and land management strategies in developed countries, as well as in developing countries. Ideally, a land administration system sits within the land management paradigm as the core infrastructure for achieving sustainable development. Figure 5 is showing the global approach to modern land administration systems. The four land administration functions, which also appear in the land management paradigm, are enlarged. Figure 5 is showing their role and subsequently they are linked with each other to support efficient land markets and effective land use management. Efficient land markets and effective land use management will provide sustainable development (Williamson et al., 2010). Land administration systems are encouraging the integration of the four land administration functions, which are shortly discussed in paragraph 2.2. Table 1 is describing the land administration functions more intensively. The integration of the four land administration functions is necessary for sustainable development.

Figure 5: The global approach to modern land administration systems



Source: Williamson et al., 2010

Table 1: A description of the four land administration functions

Land administration function	The processes and institutions related to:
Land tenure	• Securing access to land and inventing commodities in land and their allocation, recording and security. • Cadastral mapping and surveying, in order to determine the boundaries of land parcels. • Creating new properties or altering existing properties. • Transferring properties or use from one party to another party. This may be accomplished by sale, lease or credit security. • Managing doubts and disputes concerning land rights and boundaries of land parcels.
Land value	• Assessing the value of land and properties. • Calculating and gathering revenues through taxation. • Managing land valuation disputes.

	• Managing land taxation disputes.
Land use	• Controlling of land use. This may be accomplished through the adoption of planning policies and land-use regulations at local, regional and national level. • Maintaining land-use regulations. • Managing land-use conflicts.
Land development	• Building new physical infrastructure and utilities. • Implementing construction planning. • Public acquiring of land. • Expropriation. • Changing land use by granting planning permissions, building permits and land-use permits. • The distribution of development costs.

Source: Enemark, 2009

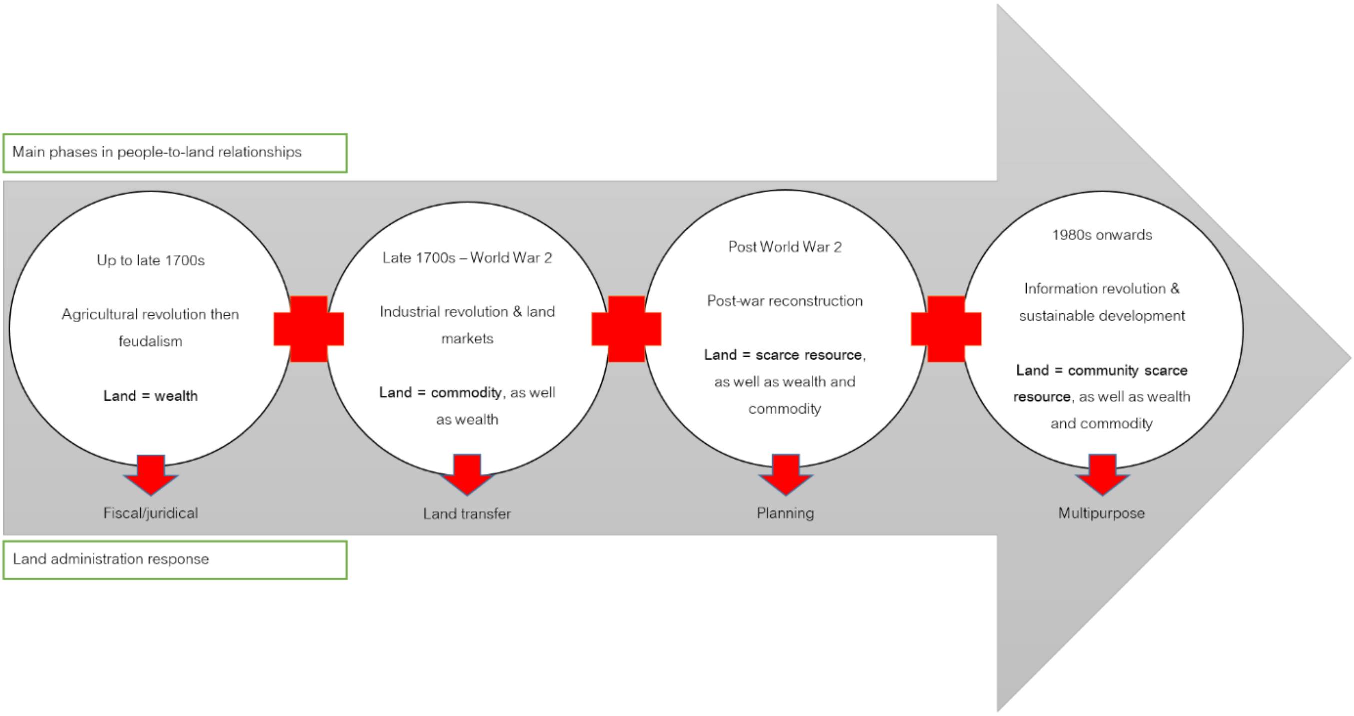
2.4 Cadastre

The cadastre is the core component of modern land administration theory. Any land administration system which is designed to support sustainable development and good governance, will make the cadastre its most important tool. A cadastre is a large-scale representation of how a community breaks up its land into land parcels (Williamson et al., 2010). The International Federation of Surveyors (FIG) provides a more complete definition. According to FIG, the cadastre is "*a parcel-based an up-to-date land information system containing a record of interest in land (i.e., rights, restrictions, and responsibilities)*" (FIG commission 7, 1995). Firstly, this paragraph will discuss the limitations of former cadastres. Subsequently, the multipurpose cadastre will be discussed.

Limitations of former cadastres

Land administration evolved over time in response to changing people-to-land relationships (see figure 6). During the days of feudalism, land was seen as primary source of wealth and the cadastre served the purposes of recording ownership and land taxation. During the industrial revolution, land was still seen as source of wealth, but also as commodity. The cadastre existed to facilitate land transfers. After the second Word War, land was seen as scarce resource. The cadastre mainly served planning purposes. Over the last decades, which can be referred to as the information revolution, land is seen as community scarce resource. The multipurpose cadastre, which will be discussed later on in this paragraph, arrived (Ting & Williamson, 1999).

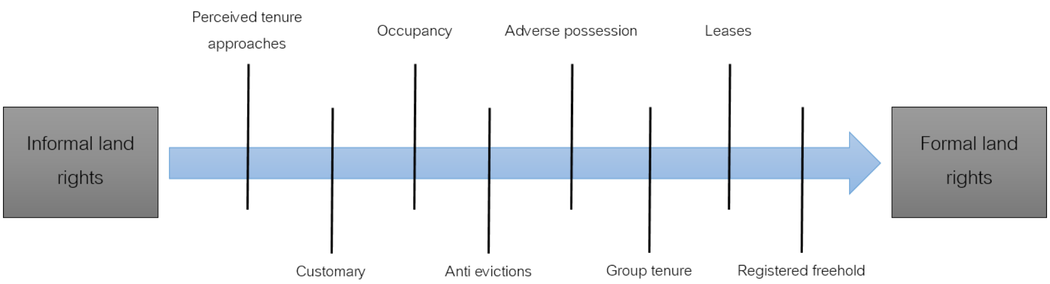
Figure 6: The land administration response to the four main stages in people-to-land relationships



Source: Williamson et al., 2010

Former cadastres (i.e. juridical, fiscal and land-use cadastres) cannot include informal and customary tenures and serve only the elite. They do not serve the millions of people, whose tenure is predominantly social rather than legal. This relates to the continuum of land rights (see figure 7). The continuum of land rights includes a variety of land tenure forms, which are considered as a continuum. The land rights of people are situated somewhere on the continuum, in between informal and formal land rights. One should take into account that the continuum of rights does not imply, that a developing country will or should necessarily develop into freehold tenure systems. The continuum of land rights is supported by the Social Tenure Domain Model (STDM). STDM, which is a specialisation of the new ISO standard on Land Administration Domain Model (LADM), provides an inclusive and generic solution for building flexible land administration systems (Enemark et al., 2014). See also Oosterom et al. (2006), Oosterom et al. (2011), Uitermark et al. (2010) and Lemmen et al. (2009).

Figure 7: The continuum of rights

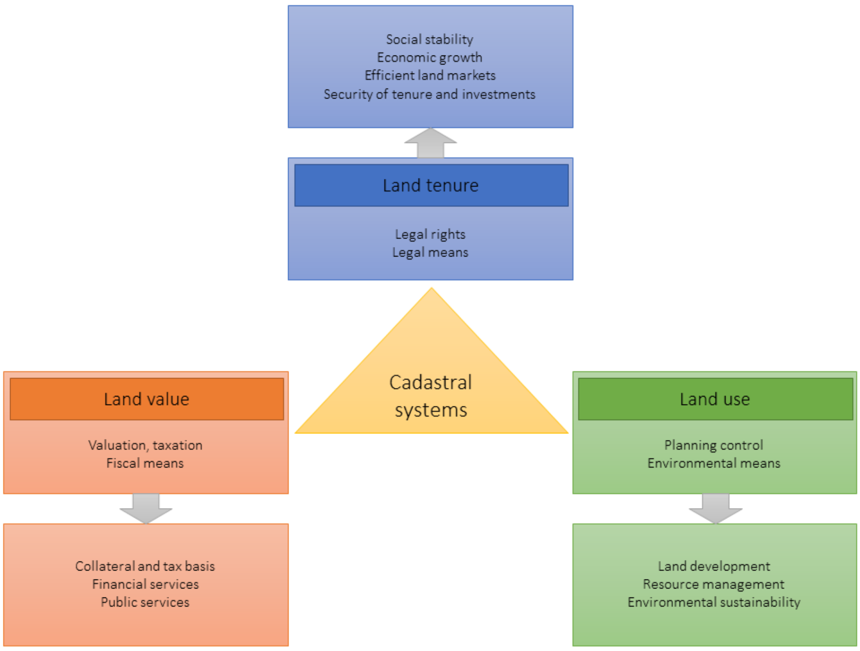


Source: UN Habitat, 2008

The multipurpose cadastre

As mentioned in the previous section of this paragraph, nowadays land is seen as a community scare resource. The response of the land administration discipline is the multipurpose cadastre. The four land administration functions of land tenure, value, use, and development are supported by the multipurpose cadastre (see figure 8). In other words, a multipurpose cadastre provides a wide range of information which is related to land (UN-ECE, 1996). Besides supporting the valuation and taxation of land and property, multipurpose cadastres do also support the present and possible future use of land (Enemark, 2005).

Figure 8: The multipurpose cadastre



Source: Williamson et al., 2010

2.5 CADASTRAL MAP

The cadastral map is one of the most important components of a cadastre and provides the spatial integrity of every land parcel within a cadastre. Since the cadastral map is a crucial component of a cadastre and a cadastre is the most important tool of a land administration system, constructing a cadastral map will support a sustainable development and good governance in developing countries. A cadastral map is "*an official map showing the boundaries of land parcels, often building on land, the parcel identifier, and sometimes references to boundary corner monumentation. Cadastral maps may also show limited topographic features*" (Williamson et al., 2010). Land parcels and their boundaries are the foundation of the cadastral map. Land rights and land use can be linked to the land parcel, as identified on a cadastral map, with the use of a unique parcel identifier. In this way, the cadastre provides a unique identification of every land parcel. The unique parcel identifier is a unique key for retrieving the attributes which are belonging to the land parcels. These attributes are stored in records and are kept separate from the map (Lemmens, 2011).

Cadastral maps require a large scale, because all land parcels have to fit the cadastral map, also smaller parcels. Normally, cadastral maps range from scale of 1:500 to 1:10.000 (Enemark & Williamson, 1996). The required scale for a cadastral map also depends on whether an area is an urban area, or a rural area. An urban area, which is densely developed, contains more and smaller land parcels. Therefore a larger scale is necessary (i.e. from 1:500 to 1:2.500. Rural areas are less densely developed. These areas contain larger land parcels. Therefore, rural areas require a smaller scale than urban areas (i.e. from 1:2.500 to 1:10.000) (Dale, 1995).

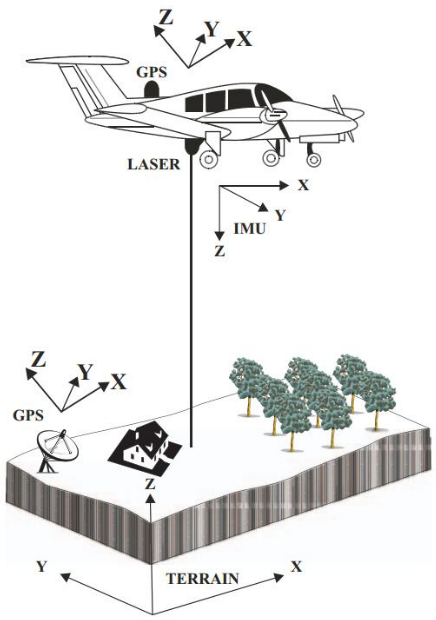
ISO 19152 is using the term spatial unit, instead of land parcel. A spatial unit is a single area (or multiple areas) of land and/or water, or a single volume (or multiple volumes) of space. Spatial unit support the registration of informal and customary rights. Land parcels do only support formal rights (ISO 19152, 2012).

3 Airborne laser scanning for general boundary based cadastral mapping

After examining the role of a cadastral map, the next step is to explain how airborne laser scanning can be beneficial for constructing a cadastral map with general boundaries. This chapter will discuss the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping. Thereby objective 2 (identify the benefits of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping) will be achieved and sub question 2 (how can airborne laser scanning be beneficial for deriving topographic features for the purpose of general boundary based cadastral mapping?) will be tackled. This chapter will explain the approach used in this MSc thesis, namely: using topographic features derived from airborne laser scanning for constructing a cadastral map with general boundaries. First of all, paragraph 3.1 will explain airborne laser scanning and its advantages. Subsequently, paragraph 3.2 will explain how the advantages of airborne laser scanning can be used for general boundary based cadastral mapping.

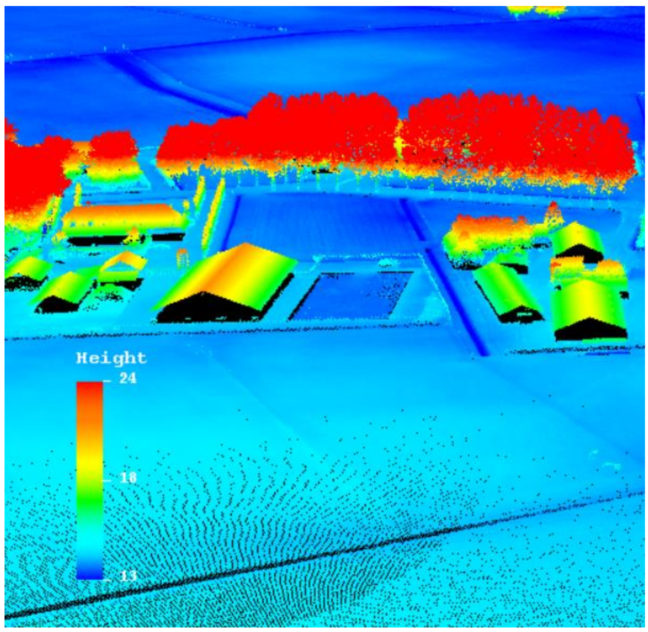
3.1 Airborne laser scanning and its advantages

Figure 9: The principle of airborne laser scanning



Source: Huurneman et al., 2009

Figure 10: Example of a point cloud, produced by airborne laser scanning

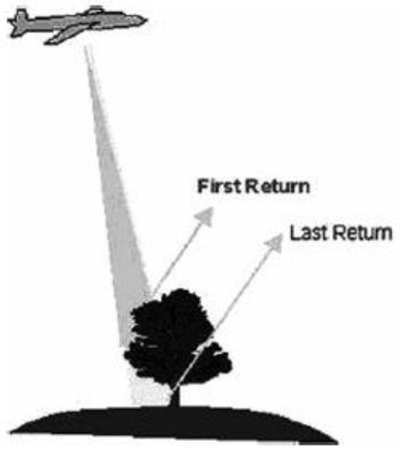


As mentioned in the introduction, airborne laser scanning is a remote sensing technology, which produces highly accurate x,y,z measurements in the form of a 3D point could dataset (see figure 10). Airborne laser scanning is a term, which is used when the laser scanner is placed on a flying platform, such as a fixed-wing aircraft or a helicopter. The point clouds produced by airborne laser scanning can be considered as highly detailed DEMs, which matches the earth's surface (Huurneman et al., 2009).

Figure 9 is showing the principle of airborne laser scanning. Airborne laser scanning is based on two major components on board of the flying platform: a laser scanner system and a combination of a Global Position System (GPS) and an inertial measurement unit (IMU):

1. **The laser scanner** emits laser pulses to the surface of the earth from the flying platform. These laser pulses are reflected by the ground and objects on the ground of the earth's surface and their return signal is recorded. For each laser pulse, one or more echoes will arise. Simple laser scanners are only able to register one return pulse for every emitted pulse. Modern laser scanner are able to record multiple echoes from the same pulse. The first return echoes will be from higher objects, such as tree canopy and building. The last returns echoes will be from the ground of the earth's surface (see figure 11) (Huurneman et al., 2009).

Figure 11: First return and last return of a laser pulse



Source: Lemmens, 2011

2. **The GPS/IMU combination** will exactly measure the position and orientation of the airborne laser scanning system. By combining GPS with IMU data, it is possible to reconstruct the flight path to an accuracy of better than ten centimetres. Measurement densities between 0.2 and about 50 points per square meter are possible, depending on the velocity and survey height of the aircraft or helicopter. A GPS station on the terrain serves as a reference station for off-line differential GPS (DGPS) calculation. DGPS is important for compensating atmospheric effects, which are disturbing the determination of the precise position. Thereby, DGPS is important for achieving decimetre accuracy (Maas & Vosselman, 2010).

Airborne laser scanning provides several advantages, which are discussed below:

- Light conditions are less critical for airborne laser scanning. A Laser scanner is an active system, which generates its own radiation. This means that data can be acquired day and night. Photogrammetry for example, makes use of light generated by external sources (Lemmens, 2011).

- Canopy penetration is another advantage of airborne laser scanning. Information of features below the tree canopy can be collected by airborne laser scanning (Maas & Vosselman, 2010).
- Another advantage of airborne laser scanning is fast data acquisition: airborne laser scanners can acquire 8000 points per second. Data about an enormous amount of land can be obtained in a relative short amount of time (Lemmens, 2011).
- In addition, airborne laser scanning provides high measurement density and high data accuracy. Point cloud densities of 30 points per square meter are reached from a helicopter. The accuracy of the x,y,z coordinates of the points of the point cloud is high: the standard accuracy is between 0.05 meter and 0.20 meter for height (z coordinate) and between the 0.2 and 1.0 meter for position (x and y coordinate) (Maas & Vosselman, 2010).

3.2 Using the advantages of airborne laser scanning for general boundary based cadastral mapping

The 3D point clouds, produced by airborne laser scanning, are containing information about the earth's surface. Laser scanner technology offers rapid high resolution capture of surface elevation data. Both the ground surface and the features on this surface are captured by airborne laser scanning (Duncan et al., 2000). In others words: airborne laser scanning is capable of capturing topographic features on the earth's surface. Airborne laser scanning may be beneficial for general boundary based cadastral mapping. After all, a general boundary coincides with a topographic feature.

One of the advantages of airborne laser scanning is fast data acquisition. Some companies, which offer airborne laser scanning data surveys, are claiming that it is possible to capture 1000 square kilometres in 12 hours (Geoshot, 2015). Since the need for cadastral maps in developing countries is urgent and majority of the developing countries in the world do not possess a cadastre or a land administration system to record land rights of people, fast data acquisition is exactly what is needed. For comparison: Zimbabwe covers an area of 390.757 square kilometres (Wikipedia, 2015b). This means that is takes 4.690 hours (390.757 / 1000 * 12) to capture airborne laser scanning data for the whole of Zimbabwe. This is approximately 195 days (4.690 / 24). This is not possible with traditional, high accurate land surveying tools, such as the total station. The data of the earth's surface can also be captured day and night, which means that cadastral mapping projects in developing countries will not be delayed because of light conditions.

The data of the earth's surface is captured with high accuracy, both for height and position. As mentioned in paragraph 3.1, the standard accuracy is between 0.05 meter and 0.20 meter for height (z coordinate) and between the 0.2 and 1.0 meter for position (x and y coordinate) (Maas & Vosselman, 2010). This is not as accurate as traditional, high accurate land surveying techniques, such as the total station. Land surveyors using GPS can yield (sub)centimetre accuracy for position (Lemmens, 2011). However, most of the time it is not necessary to measure cadastral boundaries (which coinciding with topographic features) in developing countries with (sub)centimetre accuracy. According to Enemark et al. (2014), the accuracy of land information (for example the boundaries of a land parcel), should understood as a relative issue related to the use of this information. In rural areas, a lower accuracy is allowed than in densely built up urban areas. Using traditional, high accurate land surveying techniques may be seen as end target in developing countries, however not as point of entry (Enemark et al., 2014).

Another advantage of airborne laser scanning is that it provides a height coordinate (z coordinate). Topographic features contain certain height characteristic. A dike for example appears as an elevation, where a ditch has other height characteristics, namely those of a depth. Because of these height characteristics, topographic features (which potentially could serve as general boundary) can be detected with the use of elevation data which is captured with the use of airborne laser scanning. Detecting a small dike covered with grass in a grassland area will be difficult on an aerial image, because the dike appears the same as the surrounding grassland. However, in a 3D point cloud a dike distinguishes itself from the surrounding grassland, with the use of its height characteristics. A dike is higher than the surrounding grassland, and therefore a dike can be easily detected with the use of airborne laser scanning. A condition for detecting topographic features with the use of airborne laser scanning is, that topographic features need to clearly distinguish themselves based on their height characteristics. For example: a dirt road in a rural area will be hard to detect with the use of surface elevation data, because the height characteristics of a dirt road in a rural area will be similar to its adjacent pasture or arable field. However, when a road in a city is surrounded by curb stones, the road will be easier to detect. The curb stones are higher than the road, thus a height difference will be noticed.

Figure 12 : Agroforestry in Burkina Faso; Corn is cultivated amongst palms and other trees

Source: Wikipedia, 2015a

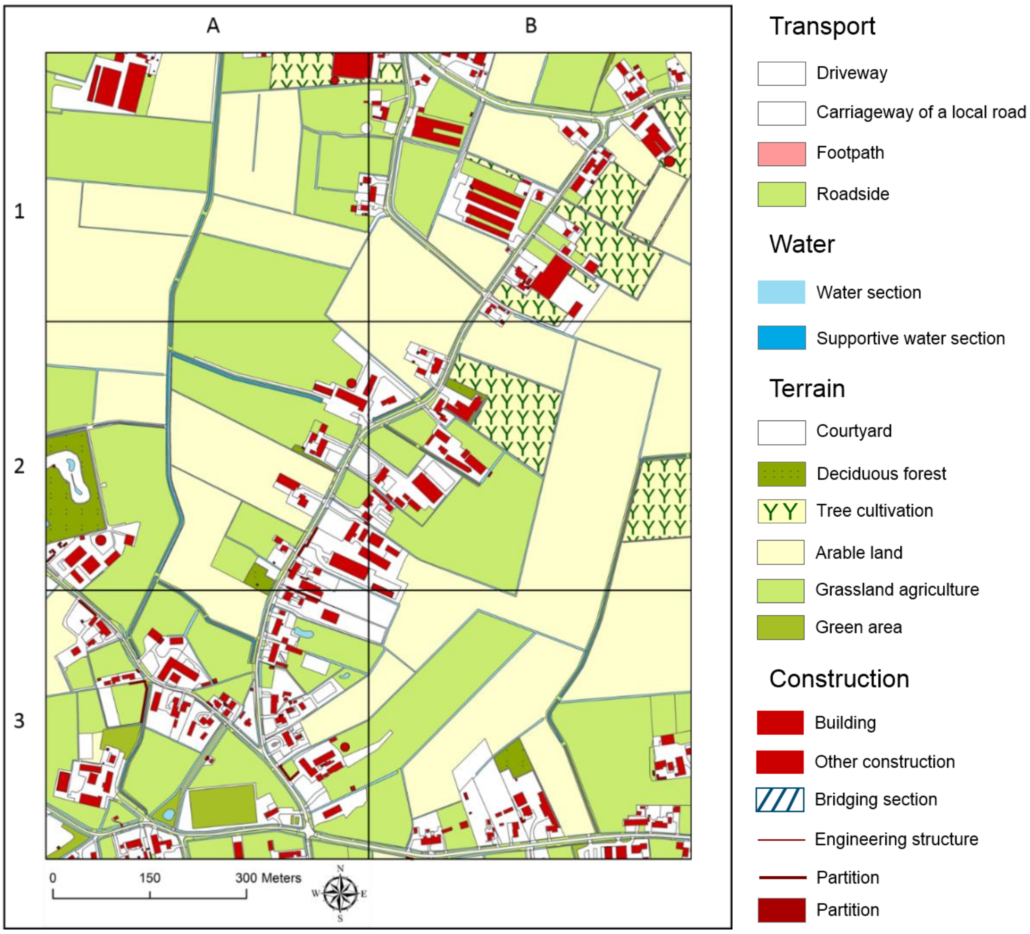
It may be possible, that a row of trees serve as topographic boundary. However, topographic features (which are potential general boundaries) may also be situated under trees. Airborne laser scanning has the ability to penetrate through canopy, which is very useful in areas where topographic features (which potentially could serve as general boundary) are situated below the canopy of trees. In order to obtain the relevant information of the earth's surface for general boundary based cadastral mapping, point cloud filtering can be applied. Several GIS software packages (for example: LAStools and ERDAS IMAGINE) are able to filter out points which represent trees. When the points which represent trees are filtered out, the earth's surface underneath these trees, containing different topographic features which may potentially serve as general boundary, will become visible. An example of an area, where the ability of airborne laser scanning to penetrate through canopy is at its full advantage, is an area with agroforestry (see figure 12). Agroforestry can be defined as "a dynamic, ecologically based, natural resource management system that, through the integration of trees in farm and rangeland, diversifies and sustains smallholder production for increased social, economic and environmental benefits" (Leakey, 1996).

4 Topographic objects serving as general boundary

After examining the role of the cadastre and its cadastral map and how airborne laser scanning can be beneficial for constructing a cadastral map with general boundaries, it is necessary to examine how often a particular topographic feature will coinciding with a cadastral boundary. One particular topographic feature will more often serve as general boundary than another topographic feature. A ditch for example, is more likely a possible boundary than a granary. In order to obtain the relevant information of the earth's (i.e. topographic features which often serve as general boundary) an overlay of a topographic map and an existing cadastral map will be performed. In this way, an indication can be provided on which particular topographic feature often coincides with an existing cadastral boundary. Thereby, objective 3 (examine how often existing cadastral boundaries coincide with particular topographic features) will be achieved and sub question 3 (to what extent do existing cadastral boundaries coincide with particular topographic features?) will be tackled. When it is known which topographic features often coincide with existing cadastral boundaries, priority can be given to search in a point cloud for particular topographic features with a high probability of being a cadastral boundary. Paragraph 4.1 will discuss the data, which is used for the overlay. Paragraph 4.2 will discuss how the overlay is performed and subsequently paragraph 4.3 will discuss the results of the overlay.

4.1 Used data

Figure 13: The BGT for the research area



The BGT and the Dutch cadastral map will be used as input data for the overlay of a topographic map and an existing cadastral map. The BGT will serve as topographic input data and the Dutch cadastral map will serve as cadastral input data. The BGT is obtained through Kadaster, which is the administrator of the BGT. The Dutch cadastral map is open data and is obtained with the use of a WMS. The cadastral map provides a graphical accuracy. The BGT can be used on a scale from 1:500 to 1:15.000 (Ministerie van Infrastructuur en Milieu, 2013).The scale range of the BGT is the reason why the BGT is used for the overlay with the Dutch cadastral map. Normally, cadastral maps range from scale of 1:500 to 1:10.000 (Enemark & Williamson, 1996). This is corresponding with the scale range of the BGT. It means that the accuracy of the topographic features of the BGT and the cadastral boundaries are similar. The BGT is a register, which contains topographic features that are present in the Netherlands. The BGT information model can be found in appendix 1. Figure 13 is showing the BGT for the research area, which is defined in paragraph 1.6.

4.2 Overlaying a topographic map and a cadastral map

The overlay of the BGT and Dutch cadastral map is performed in ArcMap. By using the PDOK-extension, a WMS can be loaded into the ArcMap environment. Public services on the map (PDOK – Dutch: Publieke dienstverlening op de kaart) provides several datasets, including the Dutch cadastral map (PDOK, 2015). The BGT consist of several shapefiles, representing the different topographic features of the BGT. These shapefiles are loaded into the ArcGIS environment with the use of the catalog window. In this way, an overlay of the BGT and the Dutch cadastral map can be performed. It should be noticed that both dataset have the same coordinate system: RD (Dutch: rijksdriehoeksstelsel) new. In this way, a good overlay can be performed.

Figure 14: BGT overlaid with the Dutch cadastral map for the research area, unit A1 (left image) and A2 (right image)

Figure 15: BGT overlaid with the Dutch cadastral map for the research area, unit A3 (left image) and B1 (right image)

Figure 16: BGT overlaid with the Dutch cadastral map for the research area, unit B2 (left image) and B3 (right image)

To perform the overlay, the research area is divided in several smaller areas of equal size, with the use of a grid. The grid is constructed in ArcMap with the use of the “grid index features” tool. In ArcMap, the whole research area is visible at a scale of 1:7.500. However, the Dutch cadastral map is only visible from a scale of 6.500 or greater. Therefore, it is necessary to divide the research area in smaller areas. The smaller areas have been assigned a code: A1, A2, A3, B1, B2 and B3 (see figure 13). The result of the overlay of the BGT and the Dutch cadastral map for each smaller research area is visible in figure 14, 15 and 16. The thicker black lines are cadastral boundaries. The legend of figure 13 is applicable for these smaller research areas. After overlaying the BGT and the Dutch cadastral map, the next step is to detect cadastral boundaries and examine which particular topographic features of the BGT coincides with the cadastral boundaries. It is also possible that there is no coincidence between a cadastral boundary and a topographic feature.

Figure 17: Counting cadastral boundaries, which coincides with particular topographic features

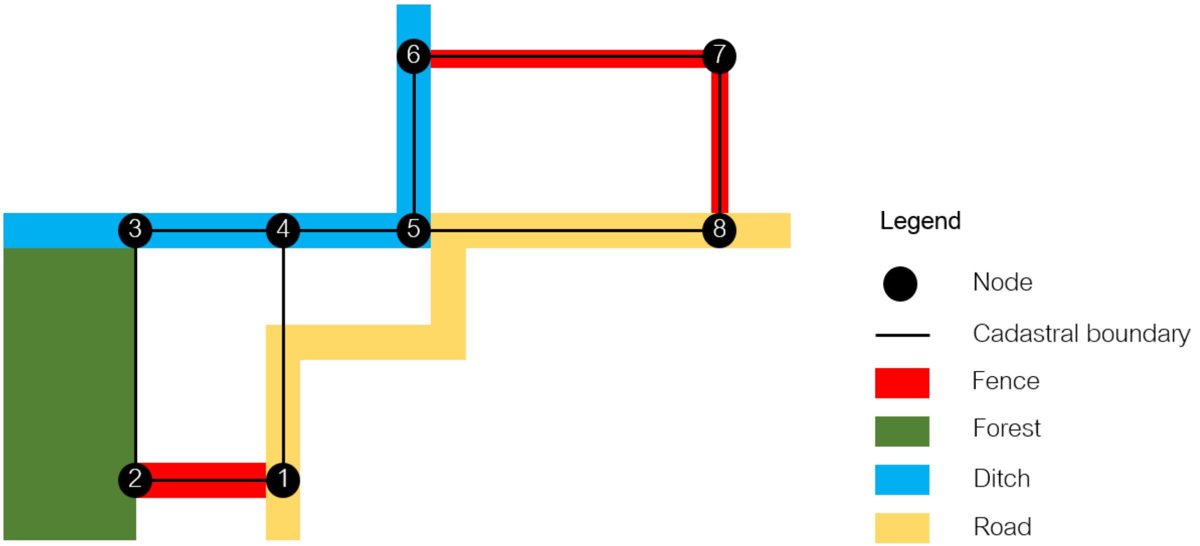


Figure 17 is explaining how the counting of coinciding cadastral boundaries and particular topographic features is performed. Figure 17 is for example showing one ditch. This ditch is serving three times as cadastral boundary: there is a cadastral boundary between node 3 and node 4, between node 4 and node 5, and between node 5 and node 6. When there is one ditch present, it does not mean that there is also one cadastral boundary. The same applies for the road, which is present in the example of figure 17. This single road serves two times as cadastral boundary: there is a cadastral boundary between node 1 and node 4, and between node 5 and node 8. Part of the road is not a cadastral boundary; not every topographic feature is a general boundary. During the counting of the coinciding of cadastral boundaries with particular topographic features, no account is taken of where a topographic feature is touched by a cadastral boundary. This might be on the side of a topographic feature, but it might as well be on the centre of a topographic feature. It should be noticed that the counting is done by hand. The Dutch cadastral map is loaded into the ArcMap environment with the use of a WMS. GIS analysis is not feasible using WMS.

After the counting of the coinciding of cadastral boundaries with particular topographic features, the statistics will be recorded in tables. This table will contain statistics on: (1) the total number of cadastral boundaries, (2) the number of cadastral boundaries which do not coincide with a topographic feature, (3) the number of cadastral boundaries which coincides with a particular topographic feature of the main group transport, (4) the number of cadastral boundaries which coincides with a particular topographic feature of the main group water, (5) the number of cadastral boundaries which coincides with a particular topographic feature of the main group terrain and (6) the number of cadastral boundaries which coincides with a particular topographic feature of the main group construction. The statistics will be analysed, in order to answer the sub question: to what extent do existing cadastral boundaries coincide with particular topographic features?

4.3 THE RESULTS OF THE OVERLAY

Table 2: The results of the overlay of the BGT and the Dutch cadastral map for the research area

	Unit						Total research area
	A1	A2	A3	B1	B2	B3	
Total number of cadastral boundaries	53	77	204	165	67	71	637
Cadastral bounday ≠ topographic feature	7	10	8	25	6	5	61
Total (% of total number of cadastral boundaries) cadastral boundary ≠ topographic feature	13%	13%	4%	15%	9%	7%	10%
Transport							
Cadastral boundary = road section	1	-	-	-	-	-	1
Cadastral boundary = roadside section	-	10	33	22	2	3	70
Total main group transport	1	10	33	22	2	3	71
Total (% of total number of cadastral boundaries) main group transport	2%	13%	16%	13%	3%	4%	11%
Water							
Cadastral boundary = ditch	29	26	79	66	27	36	263
Cadastral boundary = shore	9	13	19	-	15	4	60
Total main group water	38	39	98	66	42	40	323
Total (% of total number of cadastral boundaries) main group water	72%	51%	48%	40%	63%	56%	51%
Terrain							
Cadastral boundary = decidious forest	-	3	-	-	-	1	4
Cadastral boundary = courtyard	7	11	54	45	17	22	156
Cadastral boundary = green area	-	-	1	-	-	-	1
Cadastral boundary = transition of terrain type	-	2	-	3	-	-	5
Total main group terrain	7	16	55	48	17	23	166
Total (% of total number of cadastral boundaries) main group terrain	13%	21%	27%	29%	25%	32%	26%
Construction							
Cadastral boundary = building	-	-	8	4	-	-	12
Cadastral boundary = fence	-	2	2	-	-	-	4
Total main group construction	-	2	10	4	-	-	16
Total (% of total number of cadastral boundaries) main group construction	0%	3%	5%	2%	-	-	3%

Table 2 shows the results of the overlay of the BGT and the Dutch cadastral map for the research area defined in paragraph 1.6. The total number of cadastral boundaries in the research area is 637. A total of 61 cadastral boundaries does not coincide with a topographic feature of the BGT. This means that 10% of the cadastral boundaries in the research area does not coincide with a topographic feature. This automatically means that 90% of the cadastral boundaries does coincide with a particular topographic feature of the BGT. However, these numbers are just indications. A cadastral boundary mostly coincides with a ditch and a shore, both part of the main group water. No less than 51% of the cadastral boundaries in the research area coincides with a ditch or a shore. A courtyard is also often a cadastral boundary: 24% of the cadastral boundaries coincides with a courtyard. A courtyard is included in the counting, because a courtyard includes several topographic features (such as shrubs) which potentially could serve as boundary (Ministerie van Infrastructuur en Milieu, 2013). A roadside section is also often a cadastral boundary: 11% of the cadastral boundaries coincides with a roadside.

5 A SUITABLE POINT CLOUD DENSITY FOR DERIVING TOPOGRAPHIC FEATURES FOR THE PURPOSE OF GENERAL BOUNDARY BASED CADASTRAL MAPPING

Now that an indication is available on which particular topographic features often coincide with a cadastral boundary, it is necessary to define a suitable point cloud density for detecting these (and other) topographic features in a point cloud. This chapter will define a suitable point cloud density for deriving particular topographic features for the purpose of general boundary based cadastral mapping. Thereby, objective 4 (provide a recommendation on the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping) will be achieved and sub question 4 (which point cloud density is suitable for deriving topographic features for the purpose of general boundary based cadastral mapping) will be tackled. The Nyquist-Shannon sampling theorem is the subject of paragraph 5.1. The Nyquist-Shannon sampling theory will be used to theoretically define a suitable point cloud density for deriving topographic objects with particular widths, lengths or heights. The sampling theorem will be tested. Therefore, airborne laser data is necessary and needs to be processed. This will be explained in paragraph 5.2. In paragraph 5.3, the sampling theorem will be tested with the use of an example. Hereafter, a recommendation can be provided to developing countries on the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping.

5.1 THE NYQUIST-SHANNON SAMPLING THEOREM

The Nyquist-Shannon sampling theorem originates from the information theory. The Nyquist-Shannon sampling theorem defines the process of sampling an analogue signal into a discrete signal, without losing important information during this transaction. Usually, the sampling theorem is used to study analogue signals, such as video records. According to the Nyquist-Shannon sampling theorem, the sampling (i.e. the digitalisation) frequency of a signal (fs) should be at least twice as high as the original (i.e. the analogue) signal $(fmax)$, in order to produce a satisfying sampled record (Corsilla, et al., 2010). Figure 18 is showing the equation of the Nyquist-Shannon sampling theorem.

Figure 18: The equation of the Nyquist-Shannon sampling theorem

$$fs \geq 2\, fmax$$

Figure 19: An equation for recognising topographic features in a point cloud

$$p1 = \frac{1}{(Smallest\ dimension\ of\ a\ topographic\ object/2)^2}\ points\ per\ meter^2$$

The Nyquist-Shannon sampling theorem can also be applied for defining the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping. The equation shown in figure 19 can be used to calculate the smallest (i.e. the most suitable) point cloud density per surface unit $(p1)$, by determining the smallest dimension of a topographic object. A topographic object within a point cloud has three dimension: width, length and height. The smallest dimension of a particular topographic object in a point cloud should be used to determine the most suitable point cloud density for detecting that particular topographic feature. Suppose a hedge has a width of 0.5 meters, a length of 10 meters and a height of 2 meters. In this example, the width is the smallest dimension of the hedge. Therefore, the width of the hedge should be used to determine the most suitable point cloud density for detecting the hedge in a point cloud. The width of the hedge is 0.5 meters, thus the smallest point cloud density for detecting the hedge is 16 points per meter² ($16\ points\ per\ m^2 = \frac{1}{(0.5m/2)^2}$). The equation of Nyquist and Shannon can be applied for recognising all kind of topographic features in a point cloud.

It should be noticed that the Nyquist-Shannon does not always stand firm. Very long and thin objects, such as power lines, are also recognisable in a point cloud. According to the Nyquist-Shannon sampling theorem, very long and thin objects, should not be visible in a point cloud due to their small width. However, they are actually recognisable in a point cloud.

5.2 Obtaining the right point cloud datasets and 2.5D DEM images

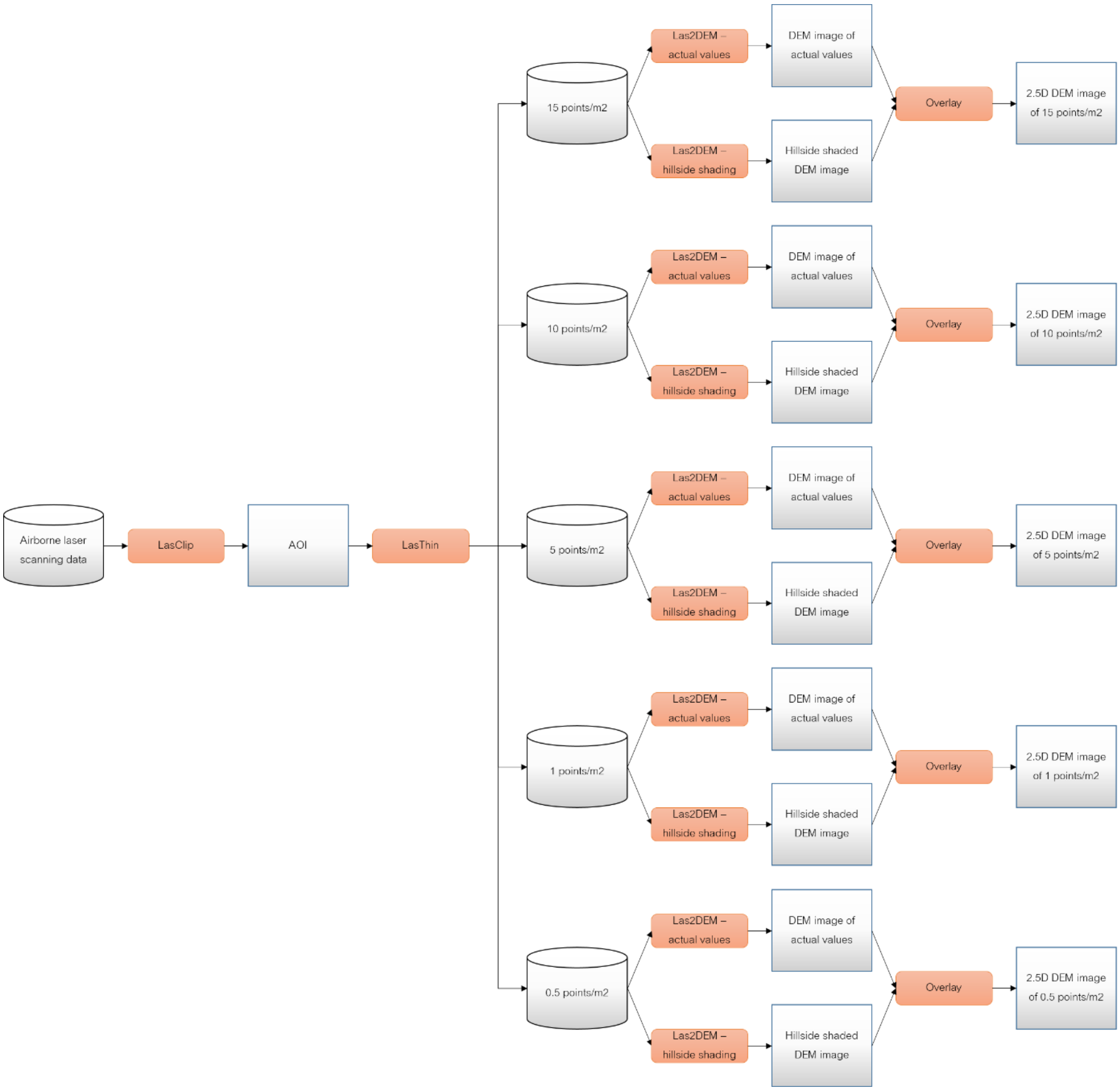
After explaining the Nyquist-Shannon sampling theorem, the sampling theorem has to be tested. In order to test the sampling theorem, the right point cloud datasets have to be obtained. Point clouds with different densities are necessary, in order to make a statement on which topographic features can be detected in a particular point cloud with a particular density. These different point clouds with different densities have to be converted to 2.5D DEM images, because 2.5D DEM images are very suitable for detecting topographic features. Figure 20 is showing how the different point cloud datasets with different densities are obtained. The figure is also showing how the 2.5D DEM images are obtained.

The input data for the workflow for obtaining point cloud datasets with a particular density and corresponding 2.5D DEM images, is airborne laser scanning. AHN 2 will be used as airborne laser scanning data. In order to obtain the complete data of AHN 2, the ground level file and the non-ground level file of AHN 2 need to be merged. Obtaining the complete data of AHN2 is necessary, because it is assumed that the input data for this workflow is complete airborne laser scanning data. The ground level file and the non-ground level file can be merged with the use of LASmerge. LASmerge is a tool which is able to read airborne laser scanning data files in several formats (LAS, LAZ, ASCII) and merges them into a single file (Rapidlasso, 2014e).

Testing the Nyquist-Shannon sampling theorem will be done for an AOI within the research area (which is defined in paragraph 1.6). The AOI have to contain different topographic features. This is necessary in order to investigate the influence of a different point cloud density on the visibility of a topographic feature with a particular geometry (i.e. plane or line). The point cloud for the AOI will be obtained with the use of LASclip. LASclip takes as input a polygon and clips away all the points of an airborne laser scanning dataset (AHN 2) that fall out of the polygon (Rapidlasso, 2015c). The polygon will be drawn with the use of the editor toolbar of ArcMap.

After obtaining the point cloud for the AOI, it is necessary to thin the point cloud in point clouds with different densities: (1) a point cloud with a density of 15 points/meter², (2) a point cloud with a density of 10 points/meter², (3) a point cloud with a density of 5 points/meter², (4) a point cloud with a density of 1 points/meter² and (5) a point cloud with a density of 0.5 points/meter². By thinning the point cloud stepwise, it is possible to compare the appearance of the same topographic features in point clouds with different densities. This process of point cloud thinning can be done with the use of LASthin, which is a simple thinning algorithm for airborne laser scanning data. By using this tool, a uniform grid will be placed over the points and within each grid cell a random z coordinate will be kept (Rapidlasso, 2014g).

Figure 20: Workflow for obtaining point cloud datasets with a particular average density and their corresponding 2.5D DEM images



The next step is to convert the point clouds with different densities to 2.5D DEM images with the use of Las2DEM. Las2DEM is able to store the actual values of the points of a point cloud into a DEM image, but the tool is also able to construct hillside shaded DEM images from a point cloud (Rapidlasso, 2015b). Both options will be used; a DEM image of the actual values of the points of a point cloud and the hillside shaded DEM image have to be constructed. These DEM images have to be overlaid in a GIS environment (ArcMap is used in this MSc thesis), whereby the DEM image of the actual values of the points of a point cloud has to be made transparent for 30%. In this way, a 2.5D-image will be obtained (Bie et al., 2011). Hillside shaded DEM images are very suitable for the visualisation of local height variations (Maas & Vosselman, 2010)

5.3 Testing the Nyquist-Shannon sampling theorem

After obtaining the point clouds with different densities and corresponding 2.5D DEM images, the Nyquist-Shannon sampling theorem can be tested. Image A of figure 21 is showing a point cloud with an average density of 15 points/meter². Different topographic features can be detected: buildings, ditches, hedges and trees. These topographic features are also visible on the corresponding 2.5D DEM image (figure 21: image B). According to the sampling theorem, topographic features, of which the smallest dimension (width, length, height) is 0.52 meters, should be able to be recognised in a point cloud with a density of 15 points/ meter² ($15\ points\ per\ m^2 = \frac{1}{0.52\ m/2)^2}$). The point clouds with an average density of 10 points/ meter² and 5 points/ m² and the corresponding 2.5D DEM images (figure 22 and 23) are able to show the same topographic features as the point cloud with 15 points/ meter² and its corresponding DEM image, although less detailed. The crown of trees in the AOI are showing that topographic features become less and less detailed, when the point cloud density reduces. In a point cloud with a density of 10 points/meter², topographic features of which the smallest dimension (width, length, height) is 0.63 meters are still visible ($10\ points\ per\ m^2 = \frac{1}{(0.63m/2)^2}$). In a point cloud with a density of 5 points/m², topographic features of which the smallest dimension (width, length height) is 0.89 meters are still visible ($5\ points\ per\ m^2 = \frac{1}{(0.89m/2)^2}$).

Figure 21:AOI with an average point cloud density of 15 points/ meter² (image A) and a corresponding 2.5D DEM image (image B)

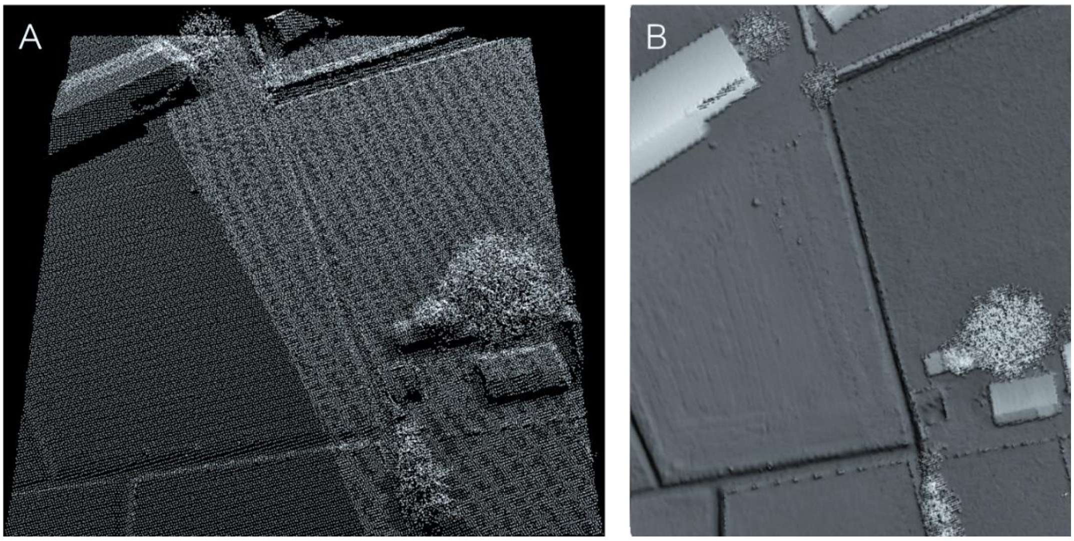


Figure 22:AOI with an average point cloud density of 10 points/ meter² (image A) and a corresponding 2.5D DEM image (image B)

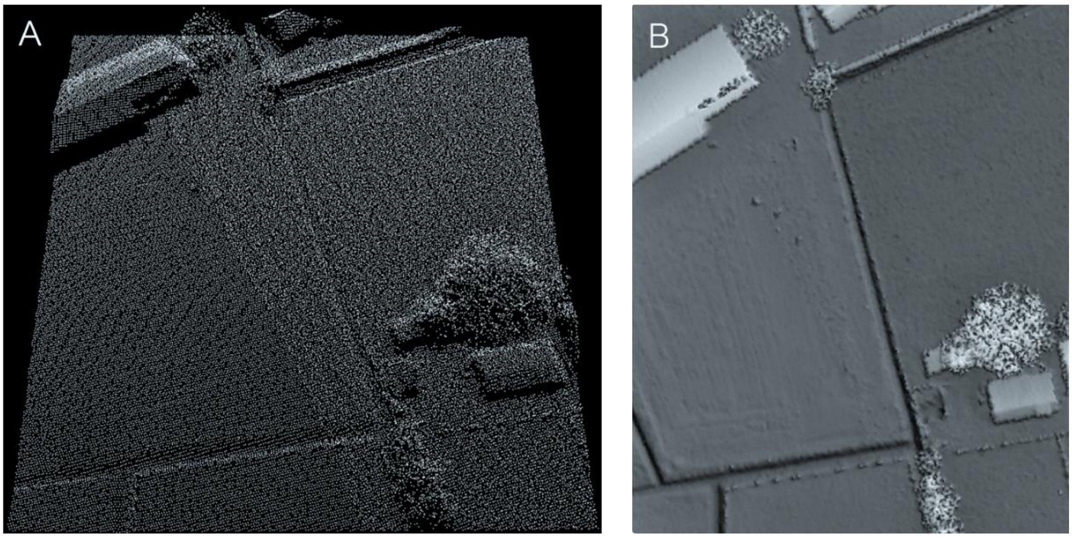
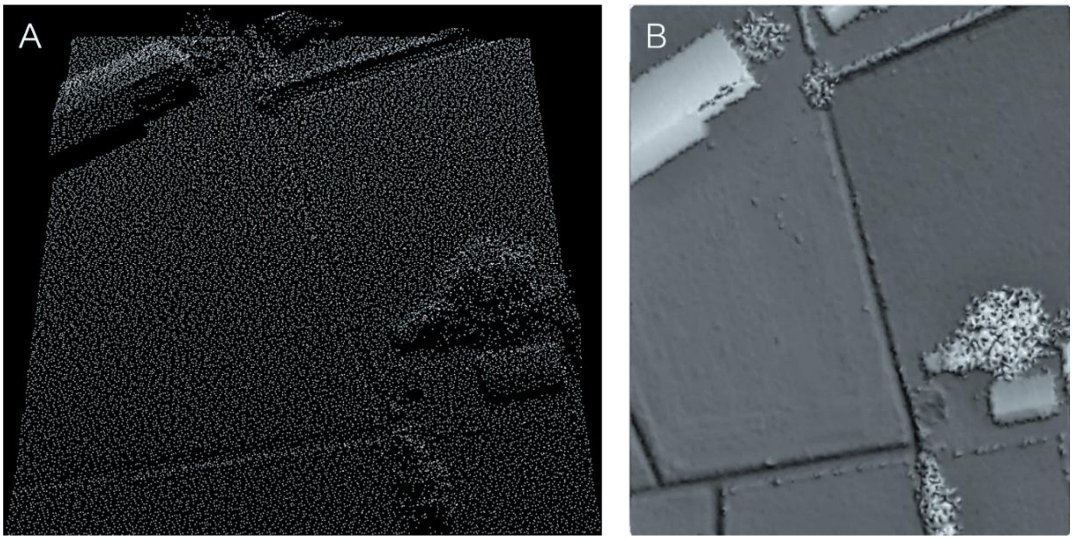


Figure 23: AOI with an average point cloud density of 5 points/ meter² (image A) and a corresponding 2.5D DEM image (image B)



When the average point cloud density is reduced to 1 points/meter² and 0.5 points/meter², it is hard to detect the same topographic features in a point cloud (see figure 24 and 25). The 2.5D DEM images of figure 24 and 25 are still showing some planes and lines, however it is impossible to recognise a topographic features in these planes and lines. The planes and lines contain too little detail, in order to recognise a particular topographic features in it. For example: roof edges of buildings are unable to be detected. In other words: due to the thinning of a point cloud, certain characteristics of topographic features are removed. This makes the topographic features unrecognisable. In a point cloud with an average density of 1 points/meter², topographic features of which the smallest dimension (width, length, height) is 2 meters are still visible ($1\ points\ per\ m^2 = \frac{1}{(2m/2)^2}$). In a point cloud with an average density of 0.5 points/meter², topographic features of which the smallest dimension (width, length, height) is 2.83 meters are still visible ($0.5\ points\ per\ m^2 = \frac{1}{(2.83m/2)^2}$).

Figure 24: AOI with an average point cloud density of 1 points/ meter² (image A) and a corresponding 2.5D DEM image (image B)

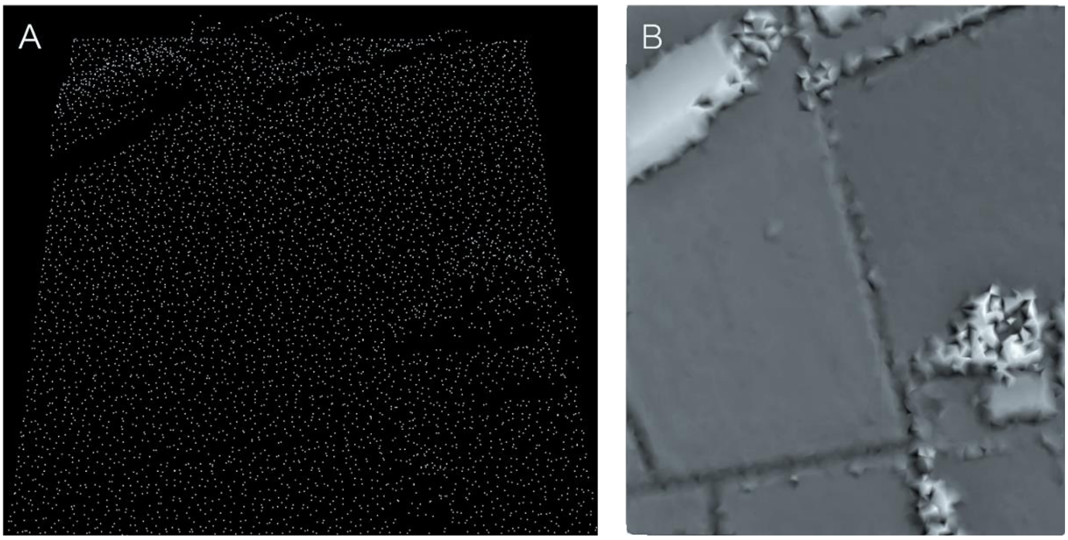
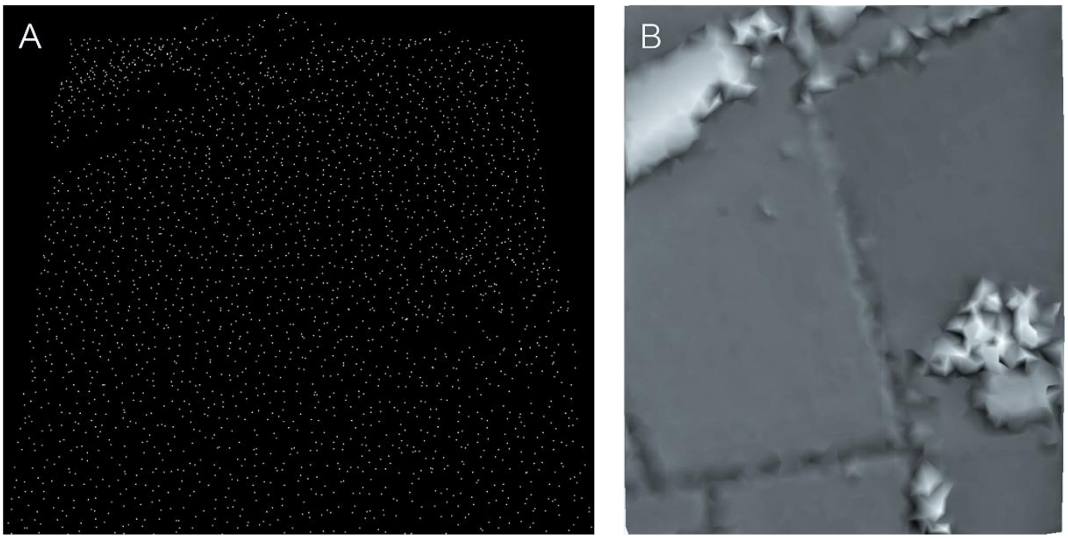


Figure 25: AOI with an average point cloud density of 0.5 points/ meter² (image A) and a corresponding 2.5D DEM image (image B)



When a (developing) country wants to order an airborne laser scanning survey for the purpose of constructing a cadastral map with general boundaries, it is recommendable to firstly determine which kind of topographic features (which could serve as general boundary) have to be derived from airborne laser scanning data. Topographic features, of which one of the dimensions (width, length, and height) is very small require a high point cloud density in order to be detected in and derived from a point cloud. An example is a fence, which has a small width. However, detecting and deriving topographic features, with larger dimensions (width, length, height), from airborne laser scanning is possible. Table 3 is showing the most suitable point cloud density for detecting and deriving topographic features with a particular smallest dimension (width, height, length). The most suitable point cloud density is calculated for a smallest dimension of 0.01 meters to a smallest dimension of 10 meters. Again, it should be noticed that very long and thin topographic features, such as power lines, are also recognisable in a point cloud.

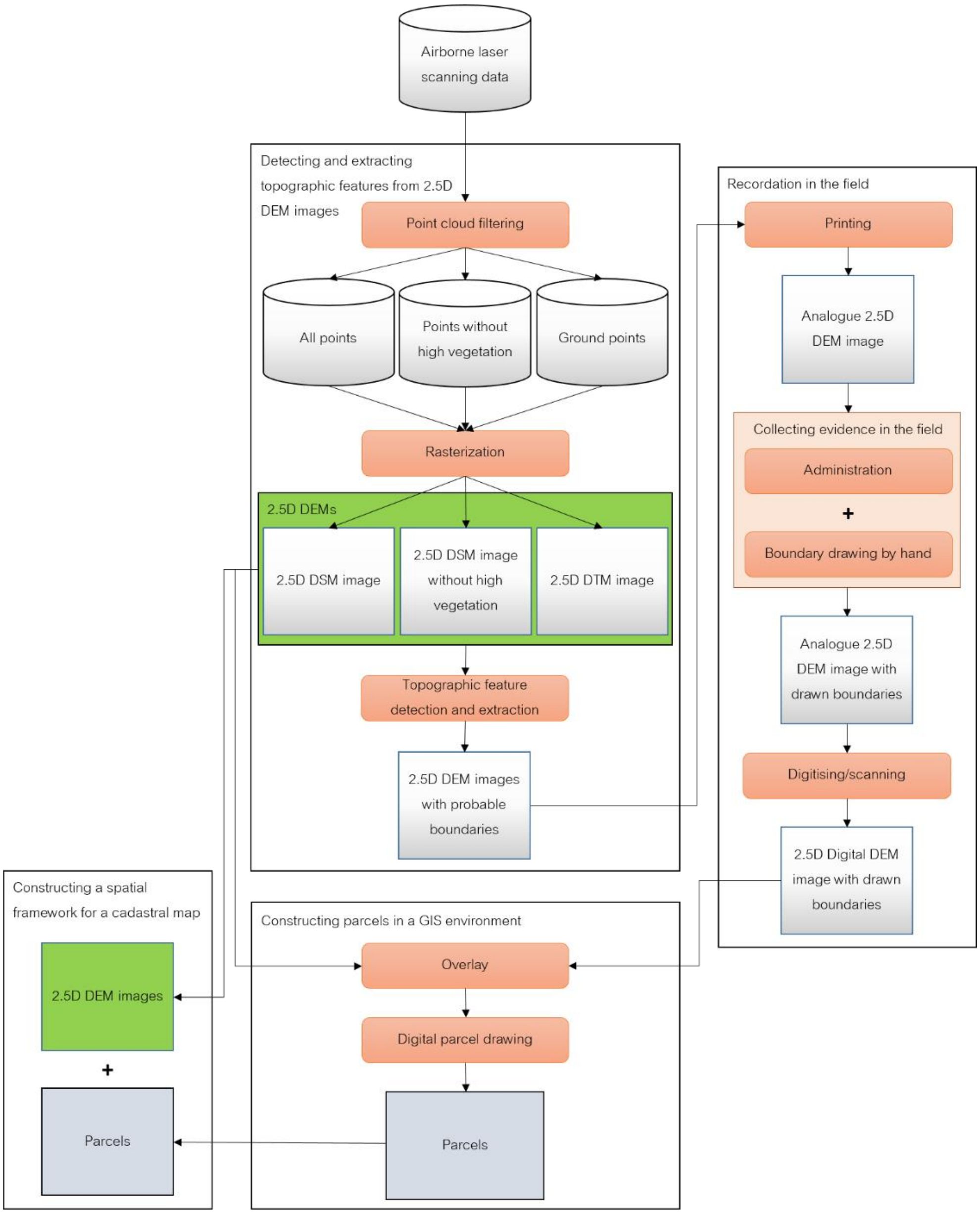
Table 3: Defining the most suitable point cloud density for detecting and deriving topographic object with a particular smallest dimension

The smallest dimension (width, length or height) of a topographic object (in meters)	The most suitable point cloud density (points/meter^2) (rounded)
0.01	40.000
0.05	1.600
0.10	400
0.20	100
0.30	44
0.40	25
0.50	16
0.60	11
0.70	8
0.80	6
0.90	5
1	4
2	1
3	0.44
4	0.25
5	0.16
10	0.04

6 A WORKFLOW FOR CONSTRUCTING A CADASTRAL MAP FROM AIRBORNE LASER SCANNING DATA

This chapter will discuss a workflow for constructing a cadastral map with general boundaries from airborne laser scanning data. Thereby, objective 5 (design a workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data) will be achieved and sub question 5 (how to construct a cadastral map with general boundaries with the use of topographic features derived from airborne laser scanning data?) will be tackled. Figure 26 is showing the workflow for constructing a cadastral map with general boundaries from airborne laser scanning data. This workflow consists of several steps: (1) detecting and extracting topographic features from 2.5D DEM images, (2) recordation in the field, (3) constructing parcels in a GIS environment and (4) constructing a spatial framework for a cadastral map. This chapter will discuss these several steps one by one.

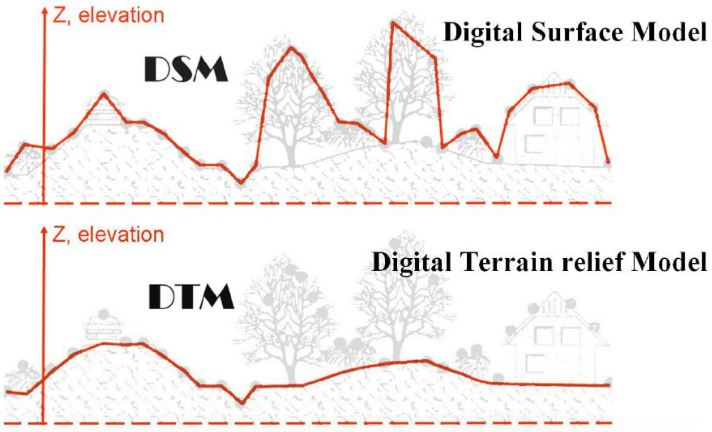
Figure 26: a workflow for constructing a cadastral map with general boundaries from airborne laser scanning data



6.1 Detecting and extracting topographic features from 2.5D DEM images

The first step towards the construction of a cadastral map with general boundaries is to detect topographic features, which may serve as general boundary, from highly detailed 2.5D DEM images. A DEM is a digital model of height, which closely matches the earth's surface. With the use of 2.5D DEM images, constructed from airborne laser scanning data, it is possible to detect change in the earth's surface caused by topographic features (Heywood et al., 2011). This is exactly what is necessary to construct a cadastral map according to the general boundary concept, because general boundaries coincide with topographic features. Three different 2.5D DEM images need to be constructed: (1) a 2.5D image of a digital surface model (DSM), (2) a 2.5D DSM image without high vegetation and a (3) 2.5D image of a digital terrain model (DTM). The difference between a DSM and a DTM is explained in figure 27. Both a DSM and a DTM can be represented by a DEM (Huurneman et al., 2009)

Figure 27: The difference between a DSM and a DTM



Source: Huurneman et al., 2009

All of the three different 2.5D DEM images will serve as one of the layers in the spatial framework for the creation of the cadastral map. The 2.5D DEM images are also constructed, to provide upgraded images which can be used in the field for recordation. In addition, the 2.5D DEM images will be used for the overlay with the 2.5D DEM images with boundaries, drawn with a pencil, which are collected in the field (these steps will be explained later on). The 2.5D DSM image without high vegetation and the 2.5D DTM image do also have other purposes:

1. The 2.5D DSM image without high vegetation needs to be constructed to detect topographic features underneath tree canopy. In the chapter 4, it was examined that the delimitations of courtyards (such as shrubs) often serve as general boundary. These delimitations can be detected from the 2.5D DSM without high vegetation.
2. A 2.5D DTM image has to be constructed to detect water sections (such as watercourses and shores) and road sections. In chapter 4, it is examined that water sections and road sections often serve as general boundary.

Detecting topographic features from 2.5D DEM images constructed with the use of airborne laser scanning data, can be seen as a smaller workflow and consist of the following steps: (1) point cloud filtering, (2) converting point clouds into 2.5 DEM images and (3) detecting and extracting topographic features from the 2.5D DEMs. These steps will be discussed in this paragraph.

Point cloud filtering

In order to construct a 2.5D DSM image without high vegetation, it is necessary to filter the points that are representing high vegetation out of the point cloud. A 2.5D DTM image can be constructed by filtering out all the points of a point cloud, except for the ground points. For the construction of a 2.5D DSM image (i.e. of all the points of the point cloud), no point cloud filtering is required.

Figure 28: Obtaining a point cloud without points that representing high vegetation and a point cloud with solely ground points

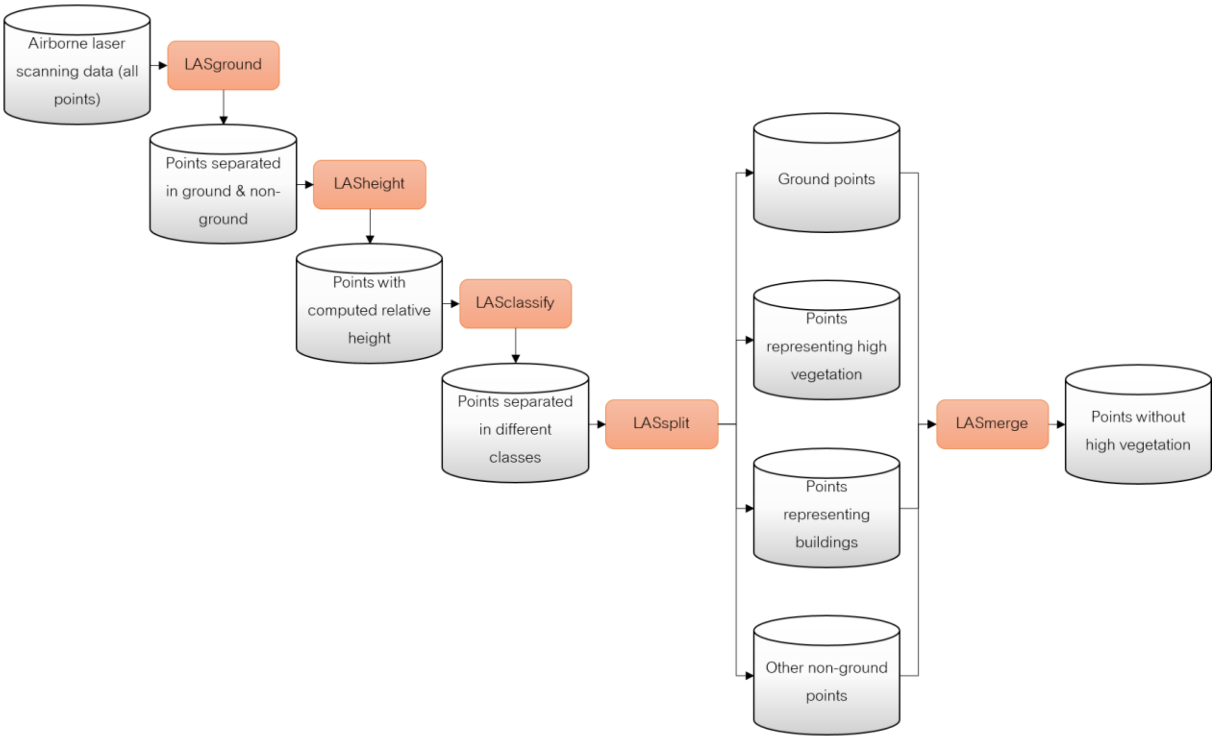
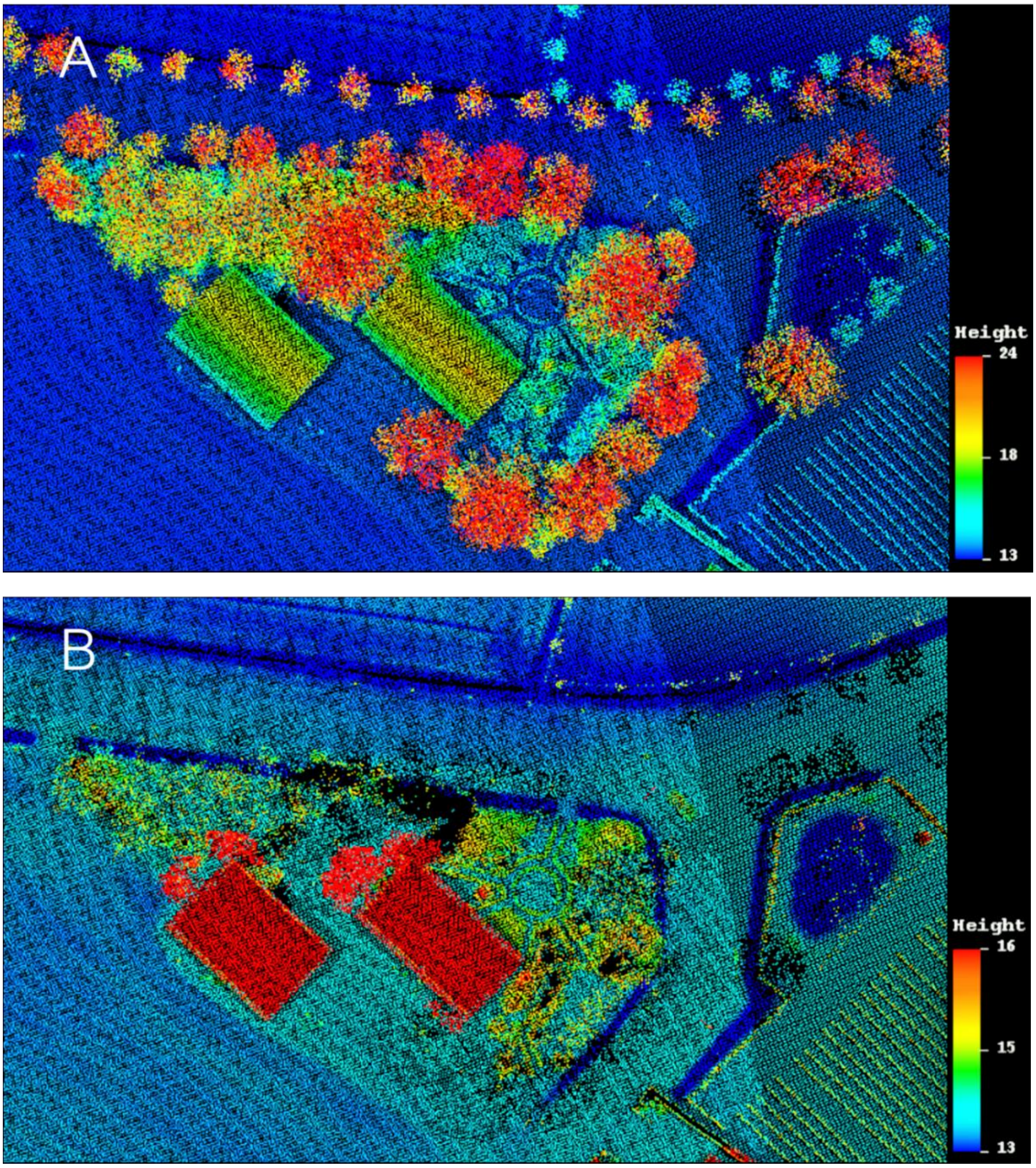


Figure 28 is showing how to obtain a point cloud without points representing high vegetation and a point cloud with solely ground points, with the use of LAStools. First of all, the airborne laser scanning data has to be automatically classified. Ground points and non-ground points have to be distinguished. This can be achieved by using LASground, which is a tool for bare-earth extraction. LASground is very suitable for the classification of ground points and non-ground points in a natural environment with a few man-made objects (Rapidlasso, 2014c). LASheight has to be used for computing the height of each point of the point cloud above the ground (Rapidlasso, 2014d). The final step of the automated classification of the point cloud is using LASclassify. LASclassify has to be used for the automated classification of buildings and high vegetation (Rapidlasso, 2014b). After the process of automated classification, the point cloud is classified in four classes: (1) ground points, (2) points which represent high vegetation, (3) points which represent buildings and (4) other non-ground points. With the use of LASsplit, it is possible to split the point cloud into four point clouds, each containing the points of one of the four classes (Rapidlasso, 2014f). In this way, the point cloud containing solely ground points is obtained. After the classified point cloud has been split, the ground points, the non-ground points and the points representing building have to be merged in order to obtain a point cloud without points representing high vegetation. The process of merging has to be executed with LASmerge (Rapidlasso, 2014e).

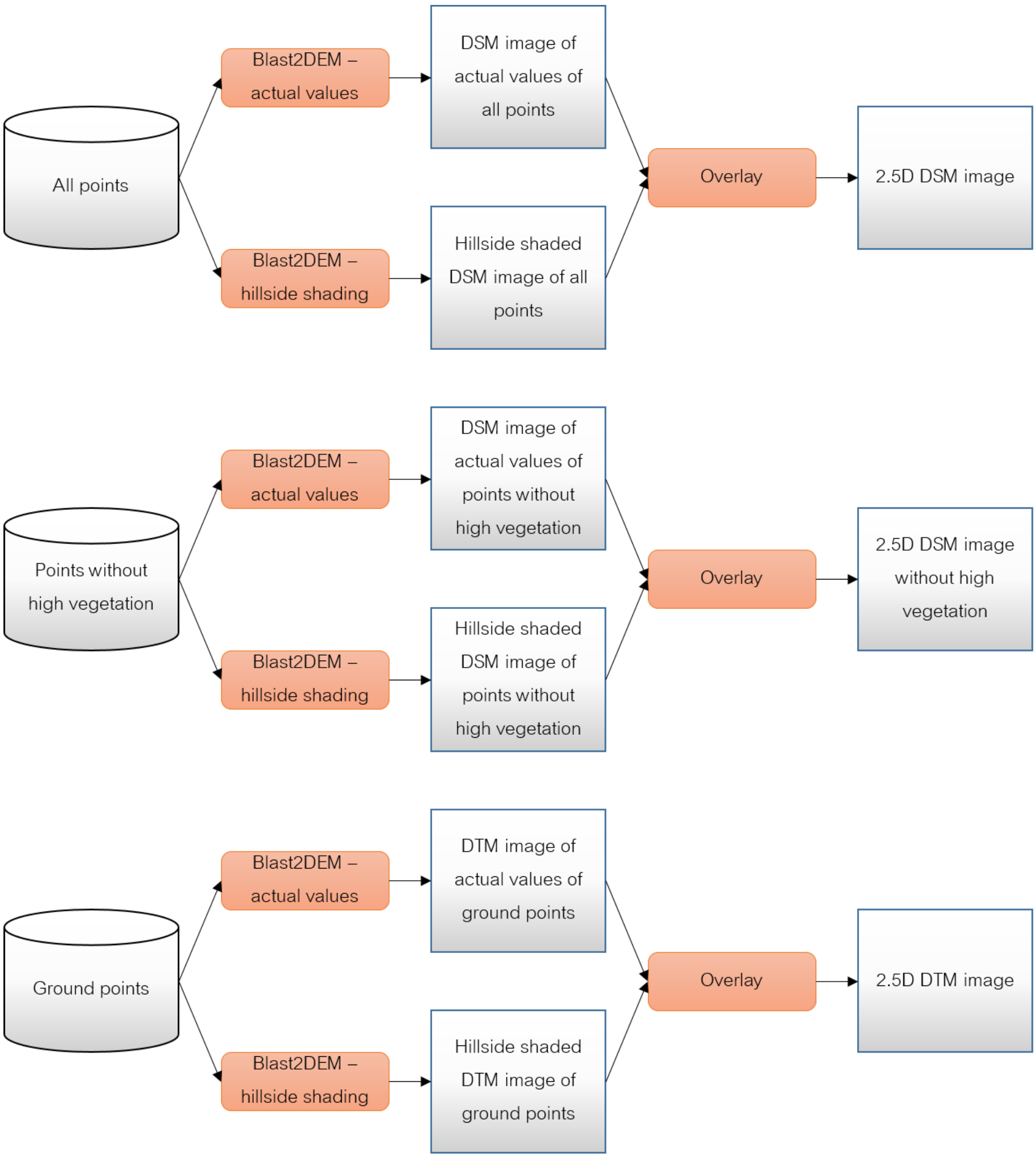
Figure 29: Top view of a point cloud containing all the points (image A) and a top view of a point cloud without points which represent high vegetation (image B)



By filtering out points with high height values, the range of height values will reduce. Topographic features, which are not visible in the point cloud containing all the points, may appear. This principle is visualised in figure 29. Image A of figure 29 is showing an image of a point cloud, which contains all the points captured by the laser scanner. The range of the height values of the points is between 13 metres and 24 metres. Image B of figure 29 is showing an image of a point cloud, where the points which represent high vegetation are filtered out. This means that the range of the height values of the points reduces, because the points with the highest height values are filtered out. The range of the height values of the point cloud, of which high vegetation is filtered out, is between 13 metres and 16 metres. Topographic features, which are not visible on image A, appear in image B due to the reduction in the range of height values. Examples of topographic features which appear in the filtered point cloud are ditches and a puddle. They appear, because high vegetation is filtered out.

Converting the point clouds into 2.5D DEM images

Figure 30: Converting the point cloud into 2.5D DEM images with the use of blast2DEM



After the process of point cloud filtering, the different point clouds have to be converted to 2.5D DEM images (the point cloud without points representing high vegetation and the point cloud containing all points have to be converted into a 2.5D DSM images and the point cloud with solely ground points, has to be converted into a 2.5D DTM images). This can be achieved with the use of the tool: blast2DEM of LAStools. First of all, blast2DEM constructs a seamless TIN (Rapidlasso, 2015a). A TIN can be described as an irregular set of height observations in a vector data model. The height observations are connected by lines. These lines together are producing an irregular mesh of triangles. The terrain surface is represented by faces and the terrain features are represented by vertices (Heywood et al., 2011). After a TIN is constructed, blast2DEM will rasterise the TIN into an image, which represent a digital elevation model (DEM) (Rapidlasso, 2015a). Rasterization is the process of converting data from vector format to raster format (Heywood et al., 2011).

Figure 30 is showing how to construct a 2.5D DSM image of all the points, a 2.5D DSM image of points without high vegetation and a 2.5D DTM image of ground points. Blast2DEM is able to store the actual values of the points of a point cloud into a DEM image, but the tool is also able to construct hillside shaded DEM images from a point cloud. Both options will be used; a DEM image of the actual values of the points of a point cloud and the hillside shaded DEM image have to be constructed. A hillside shaded DEM image is very useful for the visualisation of local height variations (Maas & Vosselman, 2010).These DEMs have to be overlaid in a GIS environment (ArcMap), whereby the DEM image of the actual values of the points of a point cloud has to be made transparent for 30%. In this way, a 2.5D image will be obtained (Bie et al., 2011). Different colour ramps are tried for the visualisation of the DEMs. Appendix 2 is showing the experiments which are performed with the different colour ramps (see figure A1, A2 and A3). The use of the “black to white” colour ramp provided the best results.

Topographic feature detection

The next step is to detect topographic features, which are probable general boundaries, on the 2.5 DEM images. In order to detect topographic features, it is necessary to know which topographic features to search for on the 2.5D DEM images. Therefore, the overlay of the BGT with the Dutch cadastral map is performed (see chapter 4). Priority should be given to search for water sections, delimitations of courtyard and road sections. However, it is also possible to detect other topographic features, which may serve as general boundary, from a 2.5D DEM image. Topographic features may also be recognised for reference purposes. Appendix 1 provides all the topographic features of the BGT. The information model of the BGT can used as indicator to detect other topographic features which may serve as general boundary.

2.5D DEM images are very suitable for detecting topographic features. However, not all topographic features can be easily detected with the use of 2.5D DEM images. By overlaying the 2.5D DEM image with the point cloud in a GIS environment (ArcMap), topographic features which are hard to recognise on a 2.5D DEM image can be detected. A part of the point cloud, which is representing a topographic feature, can be visualised by using a two-dimensional (2D) cross-sectional view (called a profile view).

Figure 31: Using 2D cross-sectional views to detect topographic features

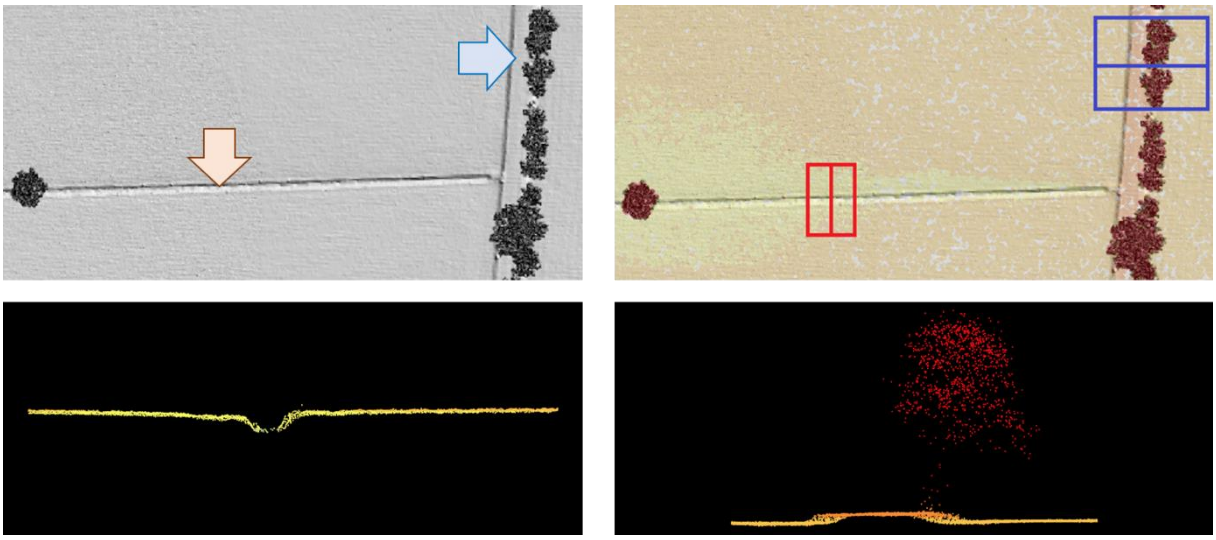


Figure 31 is showing four images. The upper left image is a 2.5D DEM image of a particular area. Two “lines” can be recognised. The red arrow is pointing to a line and the blue arrow is pointing to a line. However, solely using a 2.5D DEM image will not be sufficient to identify whether this line is a road or a ditch, or another topographic feature. Therefore, an overlay of a 2.5D DEM image with a point cloud of that particular area is necessary (upper right image). On the upper right image, the 2.5D DEM image is overlaid with a point cloud. The 2.5D DEM image is made transparent. In this way the point cloud will be visible. On the upper right image, the points near the red box are greenish. Green points are representing a relative low height. The points near the blue box are reddish. Red point are representing a relative high height. So it save to say that the line near the red box is a ditch and the line near the blue box is a road. To confirm this, 2D cross-sectional views should be created. The red box is representing a 2D cross-sectional view of one line (bottom left image). On the a 2D cross-sectional view image of the topographic feature where the red arrow points to, a depth is visible. A depth is a characteristic of a ditch. The blue box is representing a 2D cross-sectional view of the other line (bottom right image). On the 2D cross-sectional view image of the topographic feature where the blue arrow points to, an increase is visible. This has to be a road. It should be noticed, that roads can only be detected if they are surrounded by topographic features with a different height, such as ditches. When a road is not surrounded by topographic features with a different height, the road is hard to detect.

Another option to detect topographic features is to simply visualise an airborne laser scanning dataset in a point cloud viewer (for example: Quick Terrain Modeller). For this, the construction of a 2.5D DEM image is unnecessary. With the use of a point cloud viewer, it is often possible to rotate the point cloud in every direction possible. This is very helpful for detecting topographic features.

Topographic feature extraction

After detecting the topographic features, which are probable general boundaries, they have to be extracted. This process of topographic feature extraction is necessary to provide a 2.5D DEM image with vectors, which are representing probable general boundaries. This 2.5D DEM image with probable boundaries has to be taken into the field for recordation. Because this 2.5D DEM image already contains probable boundaries, less time has to be spend in the field on searching for the topographic features, which are general boundaries. This research will use the editor toolbar of ArcMap to construct a 2.5 DEM image with probable boundaries. The different 2.5D DEM images can be loaded into ArcMap. Subsequently, a vector file has to be created for the probable boundaries which have to be extracted. After constructing a vector file for the probable boundaries, an editing session can be started. Lines can be drawn for topographic features which are probable boundaries. (ArcGIS Help 10.2, 2013). In this way, a 2.5D DEM image with probable boundaries can be constructed. The vector file has to be made transparent, in order to see the topographic features, which are probable boundaries. This process can be referred to as manual topographic feature extraction.

During this research, also several attempts have been made to automatically extract topographic features. This is a very complex field of research. Experimenting with automated topographic feature extraction did not lead to the desired result. Appendices 3, 4 and 5 are explaining the experiments with automated topographic feature extraction. Multiresolution segmentation is performed in eCognition (see figure A4, A5 and A6). Segmentation algorithms are able to group points that belong together (i.e. a particular topographic feature), based on some criteria (Maas & Vosselman, 2010). Another experiment is performed with LASboundary (see figure A7). LASboundary reads laser scanning data and computes a boundary polygon for the classified points, which are representing a particular topographic feature (Rapidlasso, 2014a). The last experiment which is performed, is extracting topographic feature with the use of contour lines (or isolines) (see figure A8). With the use of the Spatial Analyst toolbox of ArcGIS, contour lines are constructed. A contour line is a line of constant elevation (Huurneman et al., 2009). For each experiments which is preformed applies: it is always searching for the right parameters, to automatically extract topographic features as good as possible.

6.2 Recordation in the field

After detecting and extracting topographic features from 2.5D DEM images, constructed with the use of airborne laser scanning data, the next step in the workflow is recordation in the field. During the “recordation in the field” part of the workflow, information on parcel boundaries and parcel ownership (and possibly other land information) will be collected from people in countries without land rights. One of the results of the “detecting and extracting topographic features from 2.5D DEM images” part of the workflow, are 2.5D DEM images with probable boundaries. These 2.5D DEM images with probable boundaries need to be printed on papers of A0 sizes. Subsequently, these printed 2.5D DEM images with probable boundaries, need to be taken into the field for the collection of information on parcel boundaries and parcel ownership (see figure 32). In this way, it can be determined whether a topographic feature extracted from the 2.5D DEM images, actually is a cadastral boundary.

Figure 32: Collecting information on parcel boundaries and parcel ownership in the field

Source: Christiaan Lemmen

With the use of instructions of right holders, boundaries can be drawn with a pencil, or a marker pen, on the 2.5D DEM image with probable boundaries. Because the 2.5D DEM image already contains possible boundaries, the process of drawing boundaries with a pencil can be accelerated. The drawn boundaries will form a parcel. The parcel will be provided with a parcel identifier. A parcel identifier is a unique key for retrieving the land rights belonging to a particular parcel (Lemmens, 2011). The unique key can be drawn on the 2.5D DEM image with probable boundaries. The land right of a particular parcel, is registered in a record and kept separate from the map. This record also contains parcel identifiers. With the use of the parcel identifier, the land rights registered in a record can be linked to the parcels on a cadastral map (Lemmens, 2011).

After the boundaries are drawn on the 2.5D DEM image with probable boundaries and the land rights of people are registered in records, the next step is to digitise the drawn boundaries from the 2.5D DEM image. In order to digitise the 2.5D DEM images with the drawn boundaries, a scanner will be used. The results are a digital 2.5D DEM images, containing the boundaries which are drawn in the field.

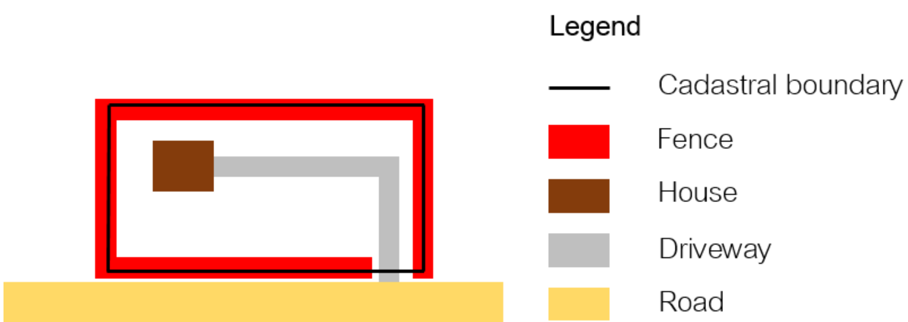
6.3 Constructing parcels in a GIS environment

After the recordation in the field is performed, the next step of the workflow is the construction of parcels in a GIS environment. The obtained 2.5 DEM images with parcel boundaries, which are drawn in the field, have to loaded in a GIS environment (for example ArcMap). The corresponding 2.5 DEM images, which are constructed during the "detecting and extracting topographic features from 2.5D DEM images" part of the workflow, also need to be loaded in to the GIS environment. Subsequently, an overlay of the 2.5D DEM images and the 2.5D DEM images containing the parcel boundaries drawn in the field, has to be performed. The purpose of the overlay is, to exactly draw the parcels in a GIS environment with the use of the parcel boundaries collected in the field. The boundaries which are drawn in the field may be rough and inaccurate. Therefore, it is necessary to redraw them in a GIS environment with the help of the 2.5D DEM images derived from a point cloud.

The first step of the construction of parcels in a GIS environment is to georeference the 2.5 DEM images with boundaries drawn in the field to the corresponding 2.5 DEM images constructed during the "detecting and extracting topographic features from 2.5D DEM images" part of the workflow. This can be achieved by using the georeferencing toolbar of ArcGIS (ArcGIS Help 10.1, 2014). First of all, a control point has to be added to a clear point of reference (such as a building) on the 2.5D DEM image with boundaries drawn in the field. Subsequently, this control points can be linked to the same point of reference on the 2.5D DEM image without the boundaries. In this way the 2.5D DEM image with boundaries will be dragged to the right position; the overlay is performed. The more control points are used, the more accurate the georeferencing process will be.

After the overlay is performed, the 2.5D DEM image with boundaries drawn in the field should be made transparent. In this way, the 2.5D DEM image without boundaries will also become visible. The next step is to draw the boundaries. This can be done with the use of the editor toolbar of ArcMap. A vector file has to be created for parcels which have to be drawn. After constructing a vector file for the parcels, an editing session can be started. Polygons can be drawn, to represent the parcels (ArcGIS Help 10.2, 2013). Attributes, such as parcel identifiers, can be added to the parcels. The parcel identifiers are referring to a record containing the land rights of people, which is kept separate from the map.

Figure 33: Constructing a cadastral boundary



It happens that the boundaries drawn in the field do not establish a closed polygon. This is because a parcel is not always completely delimited by a topographic feature. In order to construct a closed boundary, the ends of the topographic features which serve as general boundaries will be connected based on logic. Figure 33 is showing an example of such a situation. The figure is showing a parcel, which contains a house. The parcel cannot be completely delimited by fences, because otherwise no one can enter or leave the parcel. Thus, there has to be a hole in the fence. A boundary will be drawn from one end of the fence to another end of the fence. This is based on logic.

6.4 Constructing a spatial framework for a cadastral map

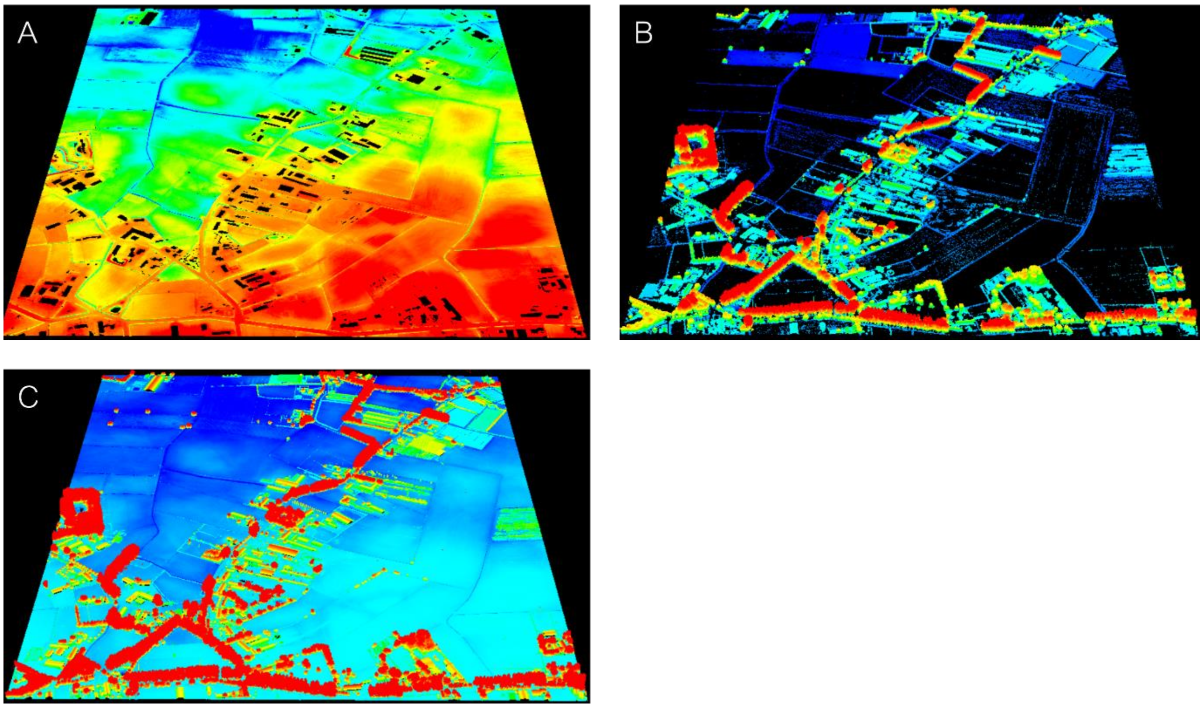
The last step of the workflow for constructing a cadastral map with general boundaries from airborne laser scanning data, is the construction of a spatial framework for a cadastral map. The spatial framework will consist of the following layers: (1) the 2.5D DSM image, (2) the 2.5D DSM image without high vegetation, (3) the 2.5D DTM image and (4) the parcel layer, containing a parcel identifier. Because the layers are part of a GIS environment, they can be switched on and off. In this way the parcel layer can be combined with the different 2.5D DEM images. This refers to the LADM, which provides an inclusive and generic solution for building flexible land administration systems (Enemark et al., 2014). See also Oosterom et al. (2006), Oosterom et al. (2011), Uitermark et al. (2010) and Lemmen et al. (2009).

7 IMPLEMENTING THE WORKFLOW

This chapter will implement the workflow for constructing a cadastral map with general boundaries from airborne laser scanning data, which is discussed in chapter 6, by using airborne laser scanning data for the research area which is defined in paragraph 1.6. Thereby, objective 6 (propose a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data) will be achieved and sub question 6 (how does a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data appear?) will be tackled. Paragraph 7.1 will discuss the data, which is used for implementing the workflow. Paragraph 7.2 will detect topographic features from 2.5D DEM images of the research area and extract topographic features, which are probably general boundaries. Paragraph 7.3 will use a 2.5D DEM image with probable boundaries, which is the result of the previous step, to draw boundaries by hand. The result is simulated data, because this data is not acquired in the field. Paragraph 7.4 will deal with the constructing of parcels in a GIS environment with the use of the 2.5D DEM images and the 2.5D DEM images containing the boundaries which are drawn by hand. Subsequently, paragraph 7.5 will deal with the construction of the spatial framework for a cadastral map. Finally, paragraph 7.6 will validate the constructed cadastral map with general boundaries.

7.1 USED DATA

Figure 34: Merging the ground level file and the non-ground level file of AHN 2. Image A: ground level file of AHN 2. Image B: the non-ground level file of AHN 2. Image C: AHN 2 complete.



The input data for the workflow for constructing a cadastral map with general boundaries is airborne laser scanning data. AHN 2 will be used as test data for implementing the workflow. AHN 2 is separated in a ground level file and a non-ground level file (such as vegetation and buildings) (AHN, 2014) In order to obtain the complete data of AHN 2, the ground level file and the non-ground level file need to be merged. The ground level file and the non-ground level file can be merged with the use of LASmerge (see figure 34). This process of merging already is executed in chapter 5. The AHN 2 dataset for the research area has an average point density of 18 points/meter². This point cloud density is suitable for detecting topographic objects of which the smallest dimension (width, length or height) is 0,47 meters ($18\ points\ per\ meter^2 = \frac{1}{(0.47m/2)^2}$). This calculation is based on the Nyquist-Shannon sampling theorem, explained in chapter 5.

The validation of the constructed cadastral map with general boundaries is based on the BGT, which is a topographic map. Chosen is to validate the cadastral map with general boundaries with the use of a topographic map, because general boundaries coincide with topographic objects, which are present on a topographic map.

Another used dataset is developed during the “recordation in the field” part of the workflow. As this part of the workflow suggests, this step should be performed in the field. However, due to the timespan of this research, simulated data will be used for this step. No instructions of right holders in the field are used for drawing the boundaries and parcels.

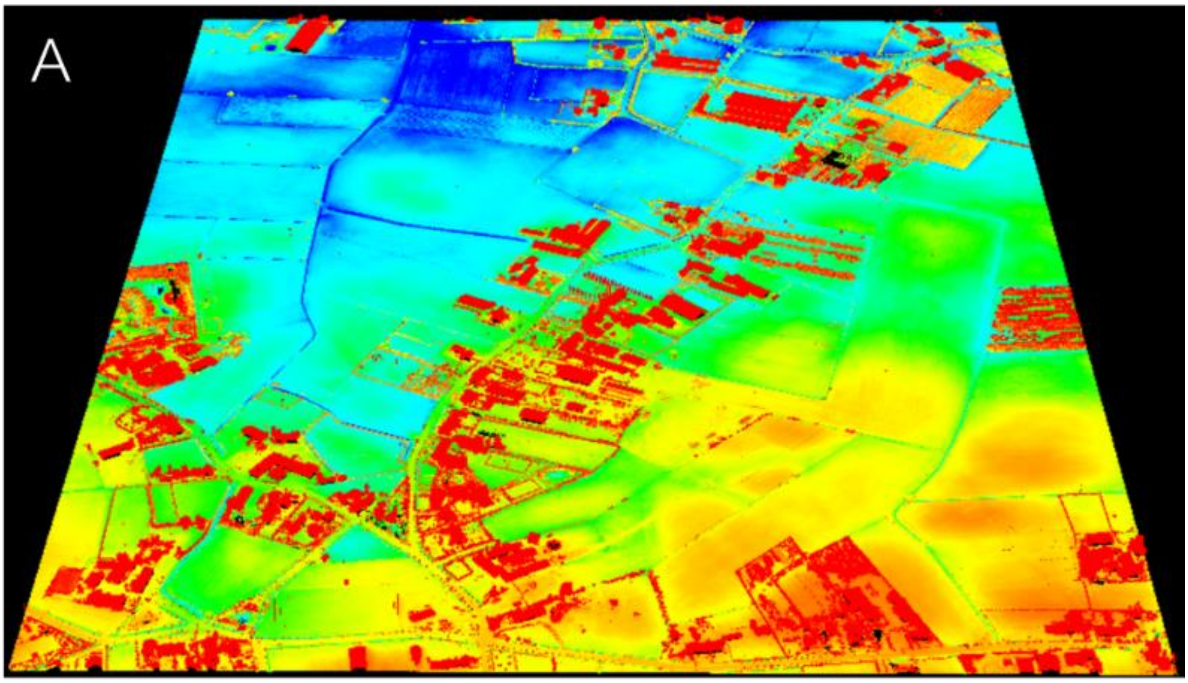
7.2 Topographic feature detection and extraction

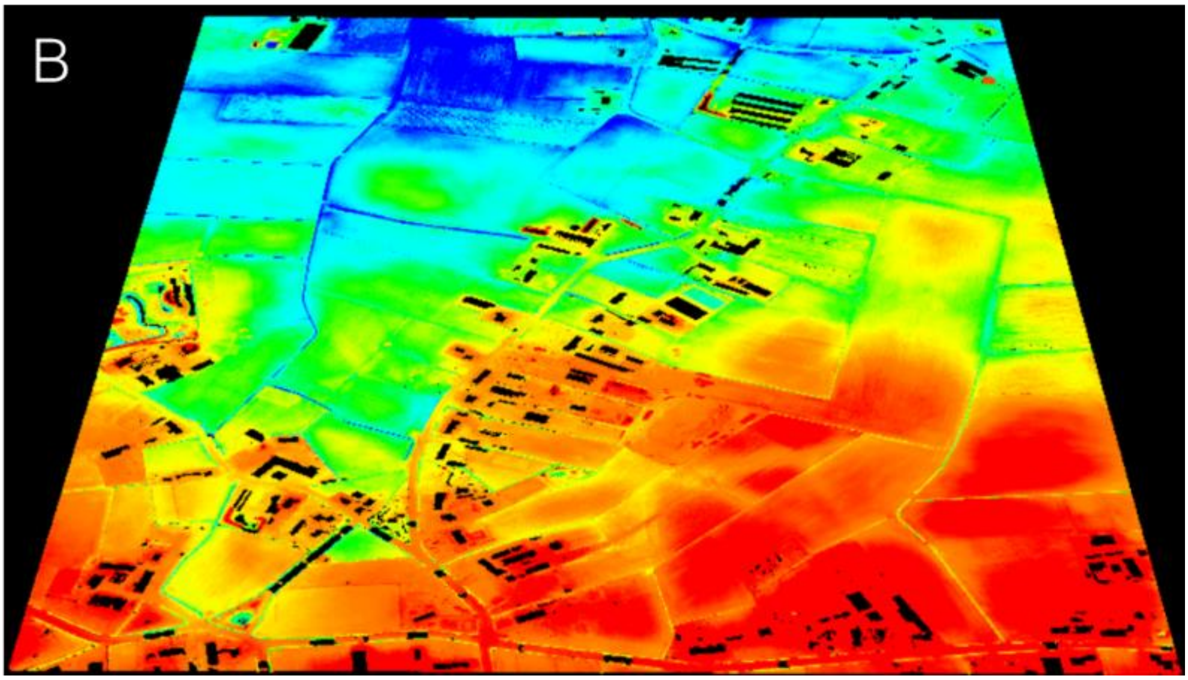
This paragraph will detect topographic features, which often serve as general boundary, from the AHN 2 dataset of the research area. Firstly, this paragraph will explain the filtering process, which is conducted on the AHN 2 dataset. Subsequently, this paragraph will discuss the process of rasterization of the filtered AHN 2 datasets. After the rasterization process, the probable boundaries will be drawn on the obtained 2.5D DEM images. The topographic features which are often topographic features are determined in chapter 4.

Filtering the AHN 2 dataset

According to the workflow, the first step in the “detecting and extracting topographic features from 2.5D DEM images” part of the workflow is point cloud filtering. Different point clouds will be used to construct 2.5D DEM images of the research area. The complete AHN 2 dataset for the research area will be used for the constructing of a 2.5D DSM image. The point cloud has to be filtered in order to obtain: (1) a point cloud without high vegetation and (2) A point cloud with ground points. The point cloud without high vegetation is used for constructing a 2.5D DSM image without high vegetation. The point cloud with ground points is used for constructing a 2.5D DTM image. Figure 35 is showing the filtered points clouds.

Figure 35: The filtered point clouds. Image A: a point cloud without high vegetation. Image B: a point cloud with ground points





Rasterization of the different point clouds

After the required point clouds are obtained, the next step is to rasterize them. According the workflow, described in chapter 6, the point clouds have to be rasterized in DEM images of the actual values of points and in hillside shaded DEM images, after which they have to be combined. The result of the combining is a 2.5D DEM image. The results of the rasterization of the complete point cloud into a DSM image of the actual values of points and into a hillside shaded DSM image, is shown in figure 36. Figure 37 is showing the 2.5D DSM image. The results of the rasterization of the point cloud without high vegetation into a DSM image of the actual values of points without high vegetation and into a hillside shaded DSM image without high vegetation, is shown in figure 38. Figure 40 is showing the 2.5D DSM image without high vegetation. The results of the rasterization of the point cloud with ground points into a DTM image of the actual values of ground points and into a hillside shaded DTM image, is shown in figure 39. Figure 41 is showing the 2.5D DTM image.

Figure 36: Image A: DSM image of the actual values of points. Image B: hillside shaded DSM image

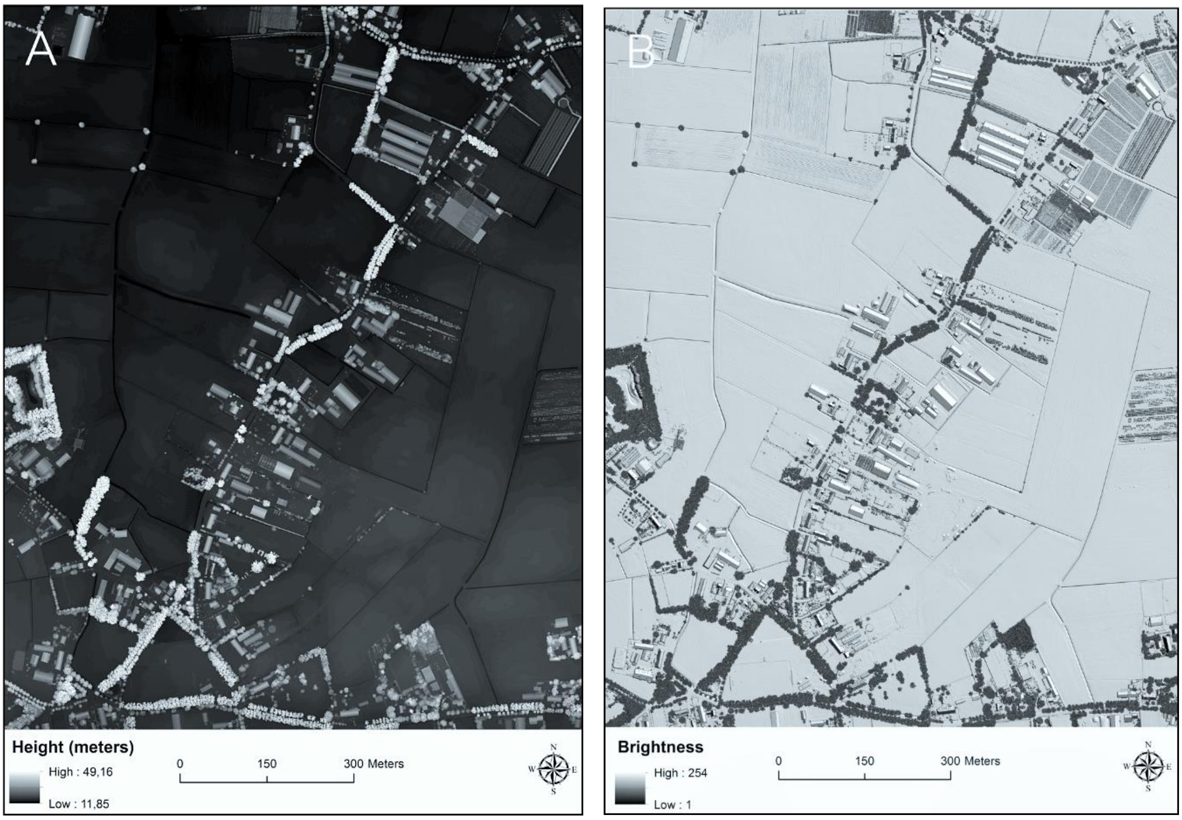


Figure 37: A 2.5D DSM image of the research area

Figure 38: Image A: DSM image of the actual values of points without high vegetation. Image B: hillside shaded DSM image without high vegetation

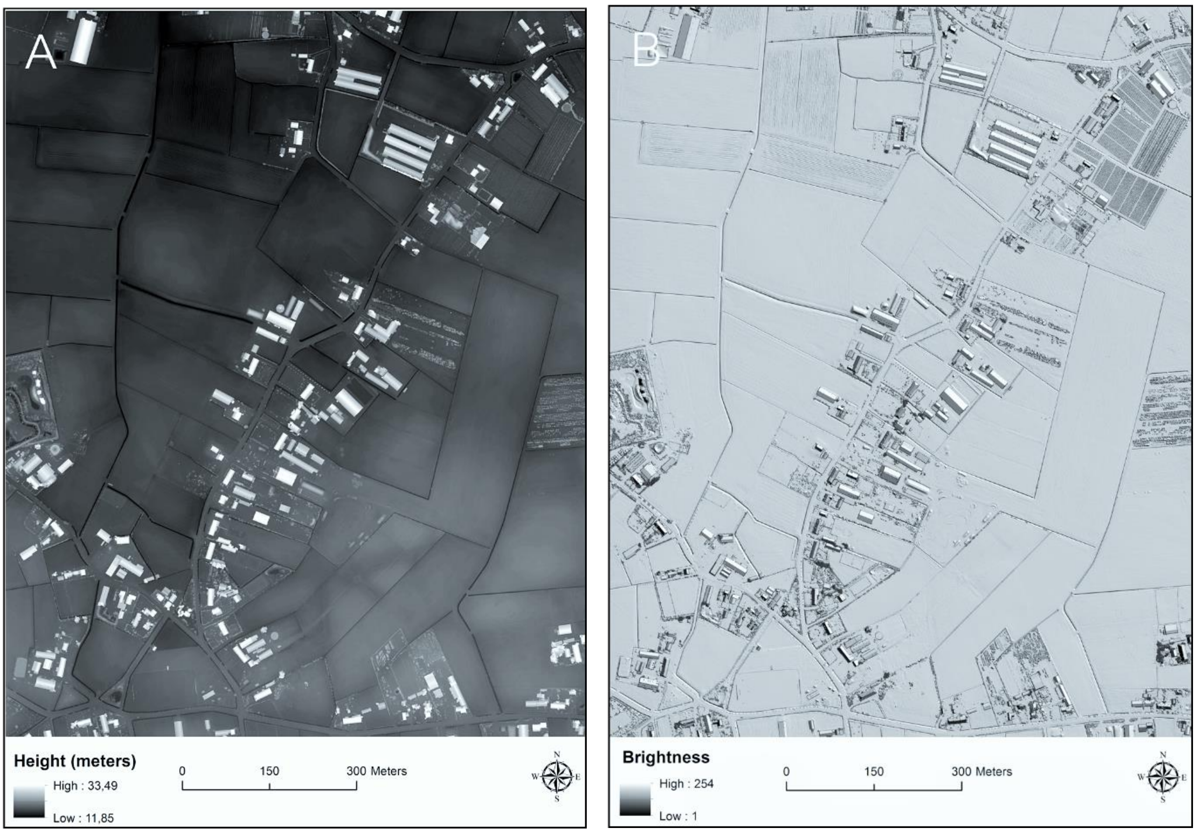


Figure 39: Image A: DTM image of the actual values of points. Image B: hillside shaded DTM image

Figure 40: A 2.5D DSM image without high vegetation of the research area

Figure 41: A 2.5D DTM image of the research area

Detecting and extracting topographic features

The next step is to detect topographic features, which are probable general boundaries, from the different 2.5D DEM images which are shown in figure 37, 40 and 41. The different 2.5D DEM images are showing several structures, which are representing the height differences caused by topographic features.

Figure 42: The 2.5D DSM image without high vegetation containing the location of the area (yellow rectangle) visualised in figure 43

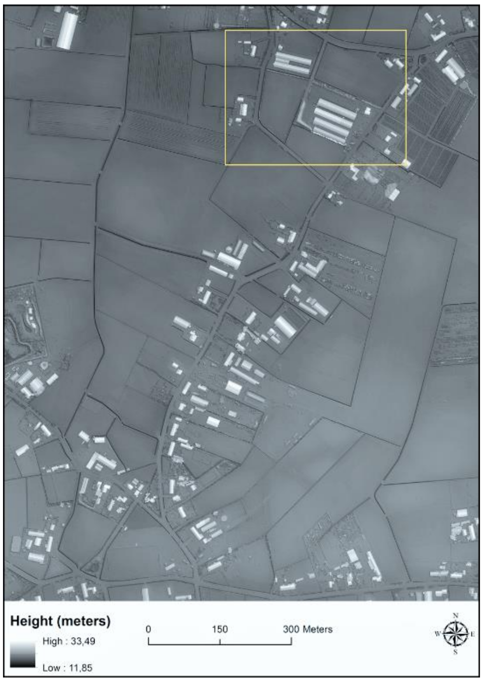
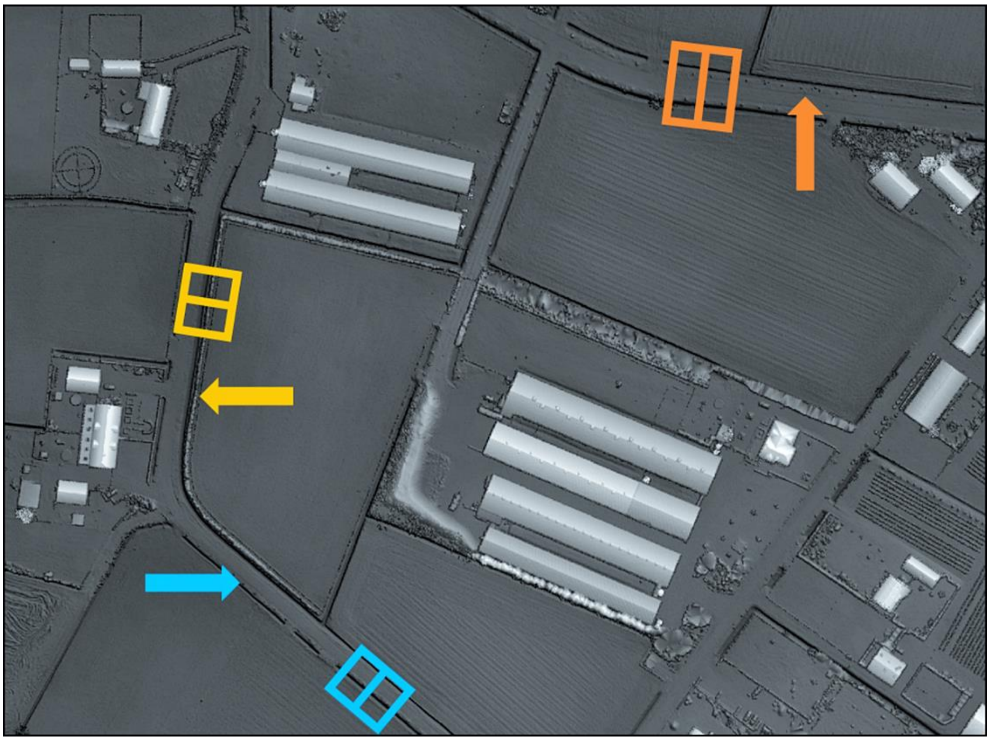
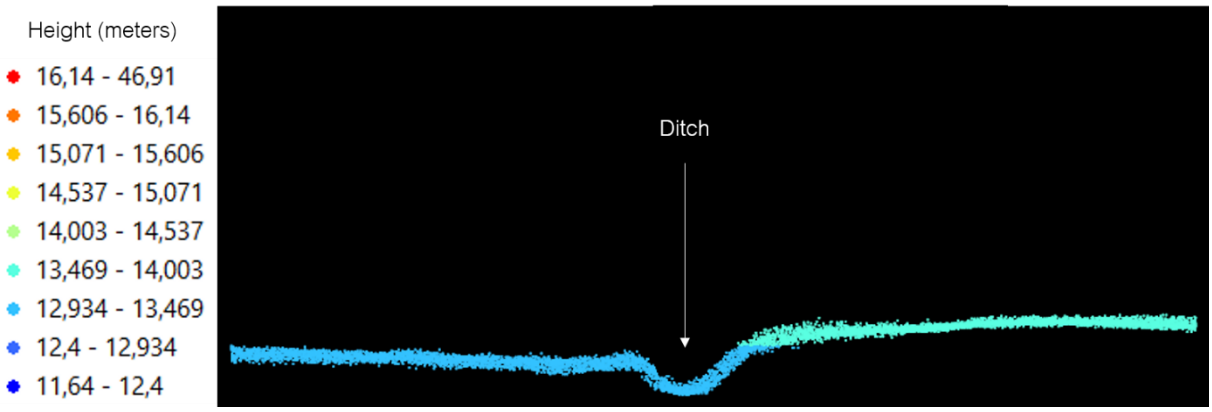


Figure 43: Zoomed in on the 2.5D DSM image without high vegetation



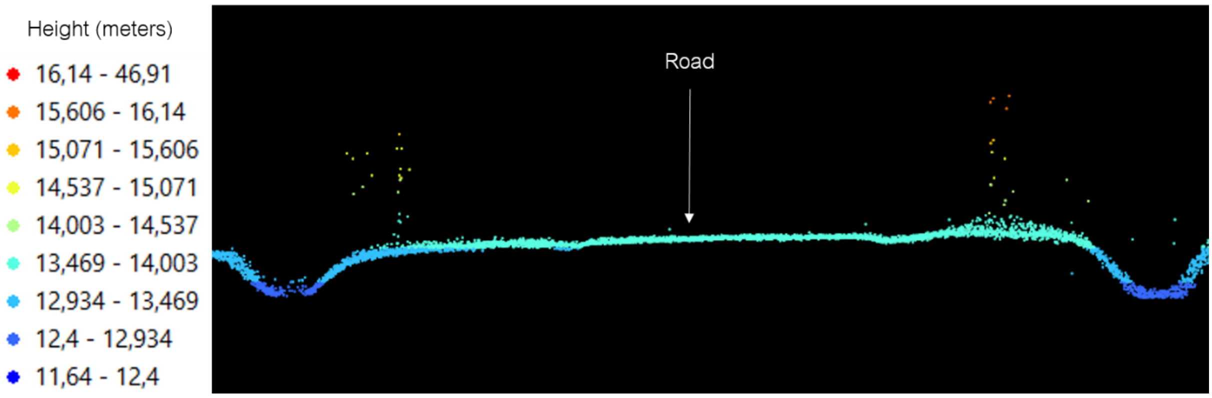
In chapter 4, it is examined that water sections, road sections and delimitations of courtyard (such as shrubs) often serve as boundary. Therefore, it is necessary to detect these topographic features. Figure 43 is showing an enlarged image of a part of the 2.5D DSM image without high vegetation. The location of the enlarged image, with respect to the 2.5D DSM image without high vegetation is shown in figure 42. Chosen is to zoom in on the 2.5D DMS image without high vegetation, because this image is able to show the water sections, road section and delimitations of courtyards (which are probable boundaries). The blue arrow on the image of figure 43 is pointing to a ditch, which is a water section. On the 2.5D DSM image without high vegetation, a ditch is visible as a black line. The black colour is indicating a depth. In order to confirm that this black line on the 2.D DSM image without high vegetation is a ditch, a 2D cross-sectional view will be constructed (see figure 44). The blue rectangle on the image of figure 43 is indicating a 2D cross-sectional view of a ditch.

Figure 44: A 2D cross-sectional view of a ditch



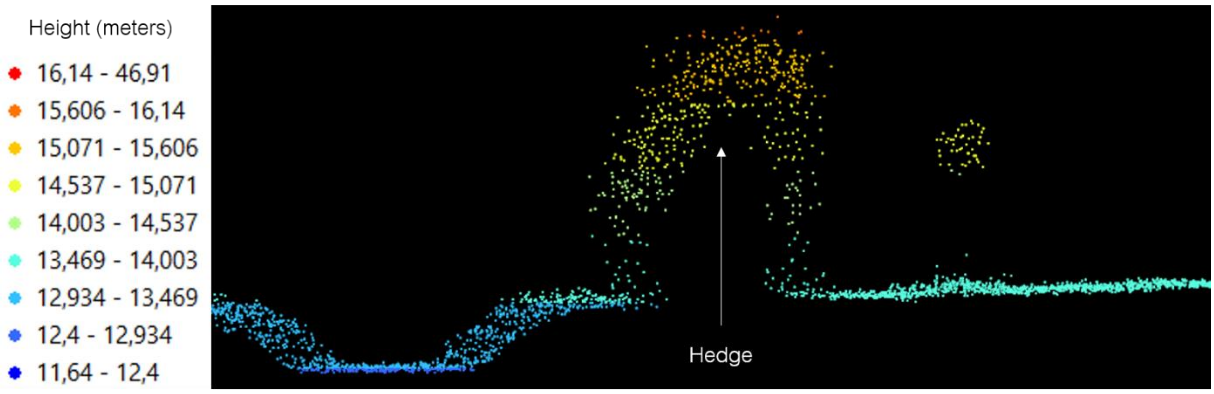
Road sections can also be detected on the image of figure 43. The orange arrow on the image of figure 43 is pointing to a road. On the 2.5D DSM image without high vegetation, a road can be detected, due to the height differences which are surrounding the road. In order to confirm that the “line” on the 2.D DSM image without high vegetation is a road, a 2D cross-sectional view will be constructed (see figure 45). The orange rectangle on the image of figure 43 is indicating a 2D cross-sectional view of a road.

Figure 45: A 2D cross-sectional view of a road



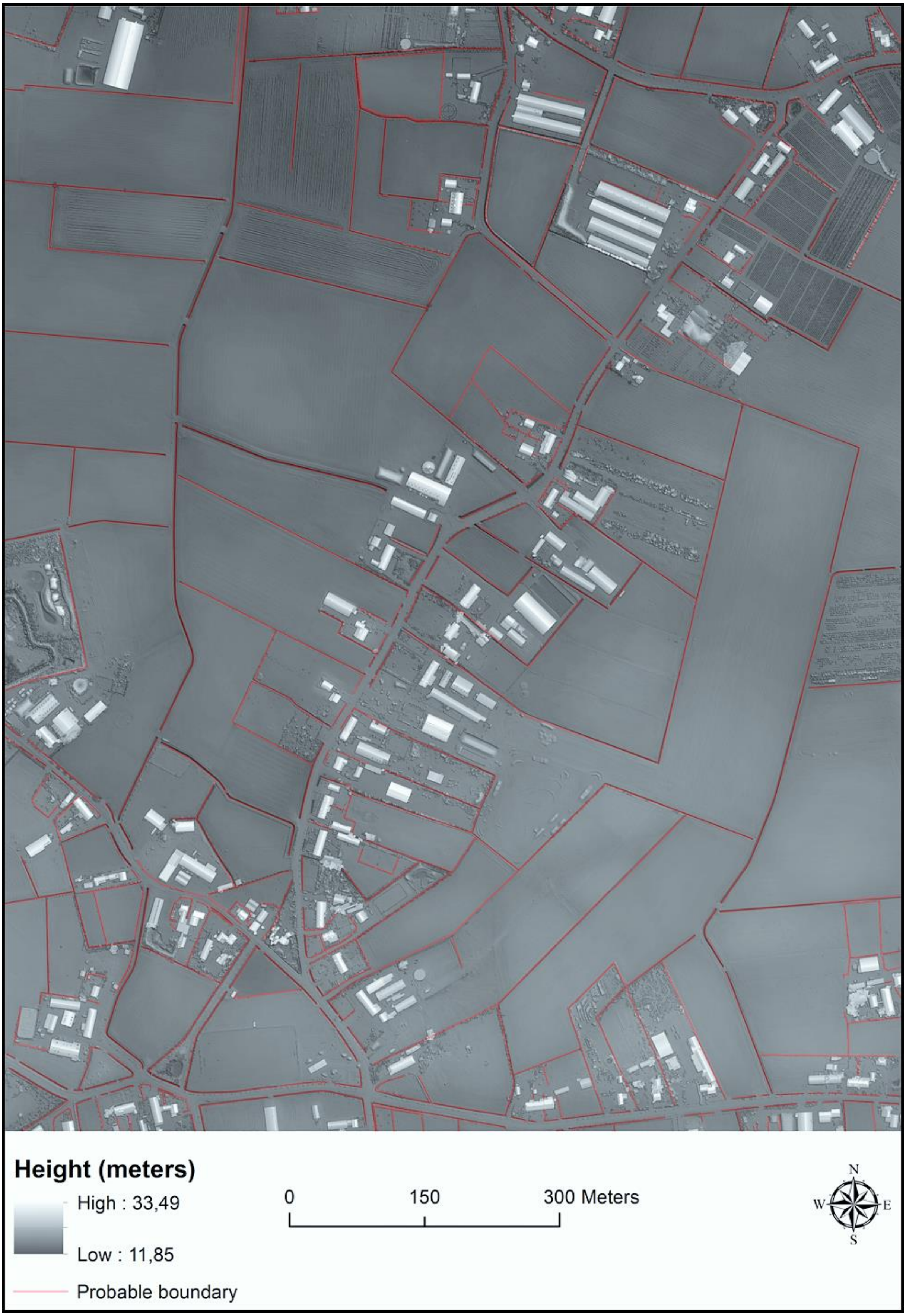
With the use of the 2.5D DSM image of figure 43, is it also possible to detect delimitations of courtyards. The yellow arrow on the image of figure 43 is pointing to a hedge. In order to confirm that the “line” on the 2.5D DSM image without high vegetation is a hedge, a 2D cross-sectional view will be constructed (see figure 46). The yellow rectangle on the image of figure 43 is indicating a 2D cross-sectional view of a hedge.

Figure 46: A 2D cross-sectional view of a hedge



After detecting topographic features, by visual inspection, on the 2.5D DEM images and with the use of the 2D cross-sectional view, it is necessary to construct a 2.5D DEM image with probable boundaries, which can be taken into the field for recordation. Lines are drawn in a GIS environment (ArcMap), which represent probable boundaries. The result is a vector file, which contains the lines of probable boundaries. This vector file with probable boundaries can be overlaid with one of the three 2.5D DEM images and taken into the field for recordation (see figure 47 on the next page). The vector file with probable boundaries is made transparent. In this way, the topographic features which are probable boundaries are also visible. In the field, it is possible to make a statement whether a probable boundary on the image is actually a boundary.

Figure 47: The 2.5D DSM image without high vegetation, containing lines which represents probable boundaries



7.3 SIMULATING THE PROCESS OF RECORDATION IN THE FIELD

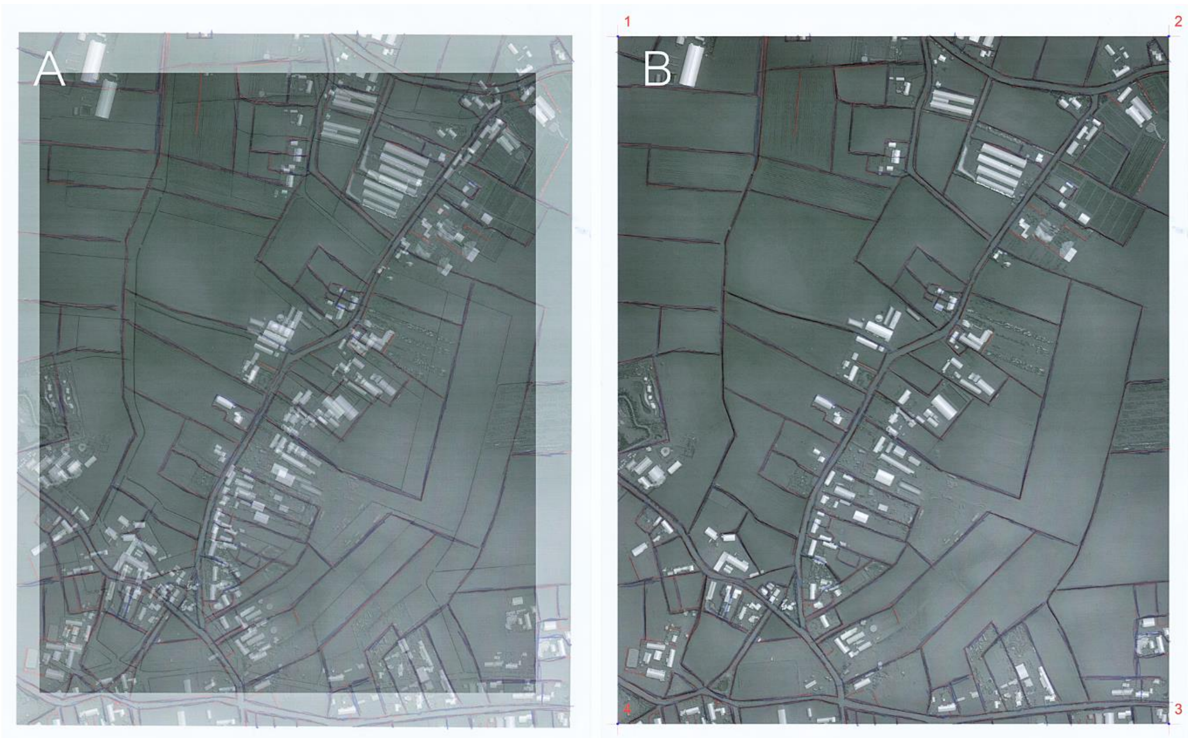
When the construction of the 2.5D DEM image with probable boundaries is finished, the next step is to take the image into the field and draw the boundaries of parcels with the use of a pencil or marker pen. One of the purposes of the construction of the different 2.5D DEM images, is to provide upgraded images which can be used in the field for recordation. For the recordation in the field, a choice can made between the different 2.5D DEM images with probable boundaries. It is also possible to take all the images into the field. However, what matters is that there are enough upgraded images available for the detection of topographic features, which could serve as general boundary.

Figure 48: A scanned 2.5D DSM image without high vegetation with boundaries drawn with a pencil

This research will not deal with recordation in the field, but it will use simulated data. Chosen is to use the 2.5D DSM image to draw boundaries on with a pencil, because the 2.5D DSM image contains water sections, road sections and delimitations of courtyards (these topographic features are often general boundaries). The 2.5D DSM image without high vegetation with probable boundaries is printed and subsequently boundaries are drawn with a marker pen. This process is executed without the use of instructions of right holders. It should be noticed that no parcel identifiers are assigned to the parcels. There are no real people, so no land rights have to be registered in records and linked to a parcel. Another difference with the instructions of the workflow, is that the 2.5 DSM without high vegetation is printed on A4 format and not on A0 format. Printing the 2.5D DSM image without high vegetation on A4 format will do for a small research area, such as the research area used in this MSc thesis. However, when the research area becomes larger, A0 format should be used. After the boundaries are drawn with a pencil on the 2.5D DSM image without high vegetation, the image will be scanned and is ready to loaded into a GIS environment. Figure 48 is showing the scanned 2.5D DSM image without high vegetation with boundaries drawn with a pencil.

7.4 Constructing parcels in a GIS environment

Figure 49: Overlaying the 2.5D DSM image without high vegetation with drawn boundaries with the corresponding 2.5D DSM image without high vegetation (image A), and georeferencing the images with the use of control points (image B)



After the 2.5D DEM image with drawn boundaries in the field in obtained, it has to be loaded into a GIS environment (ArcMap for example) together with the corresponding 2.5D DEM image without boundaries. The two images have to be overlaid, to exactly draw the parcels in the GIS environment with the use of the parcel boundaries, which are collected in the previous paragraph. The first step is to georeference the 2.5D DSM image without high vegetation with drawn boundaries to the corresponding 2.5D DSM image without high vegetation. This can be done with the use of the georeferencing toolbar of ArcMap. Control points are added on corners of both images (see figure 49). Control points can also be added to clear points of reference, such as buildings. In order to perform a good overlay, the 2.5D DSM image without high vegetation with drawn boundaries is made transparent. The next step is to construct the parcels with the editor toolbar of ArcMap. The constructed parcels are shown in figure 50.

7.5 The spatial framework for a cadastral map

Figure 50: The constructed cadastral map, according to the general boundary concept

Figure 50 is showing the result of the parcel drawing in the GIS environment. The drawn parcels are overlaid with the 2.5D DSM image without high vegetation. Both layers are part of the spatial framework for the cadastral map. The other layers of the spatial framework for the cadastral map are the 2.5D DSM image and the 2.D DTM image. The layers can be switched off and on in the GIS environment. The 2.5D DSM image without high vegetation is very suitable as base layer for the cadastral map, because several topographic features (for example buildings) which can be used as reference points.

7.6 Validating the constructed cadastral map with general boundaries

Figure 51: Overlay of the BGT and the constructed cadastral map with general boundaries

The validation of the constructed cadastral map with general boundaries is performed with the use of a topographic map for the research area, namely the BGT. The BGT dataset is already used in chapter 4. In order to perform the validation, the parcels constructed with the use of airborne laser scanning data and the BGT need to be overlaid in a GIS environment (ArcMap for example). The overlay is shown in figure 51. With the use of this overlay, a visual comparison can be made. The legend of the BGT, is displayed in figure 13. The boundaries of the parcels are made transparent, in order to see the topographic features with whom they coincide.

The boundaries and parcels constructed with the use of airborne laser scanning data, are often coinciding with topographic features. This means that the extraction of topographic features, which are serving as general boundary, from an airborne laser scanning dataset has succeeded for the most part. However, not all boundaries and parcels are coinciding with the topographic features of the BGT. Sometimes, a boundary of a parcel does not coincide with a topographic feature. A reason for this might be that the topographic feature, with whom the boundary coincide, is not included in the BGT.

8 CONCLUSION

The goal of this MSc thesis is to investigate the suitability of airborne laser scanning for deriving topographic features for the purpose of general boundary based cadastral mapping. The goal of this research is devised for the benefit of countries which have an urgent need for a cadastral map. This goal has resulted in the following research question: to what extent is airborne laser scanning suitable for deriving topographic features for the purpose of general boundary based cadastral mapping? In order to answer this question, six objectives and corresponding sub-questions are defined.

The first objective is to examine the role of the cadastre and its cadastral map, which are the core components of any land administration system. This is done with the use of a literature review. Nowadays, sustainable development has emerged as the major driver for land administration. The cadastre, which is a register of land information, has developed itself towards a multipurpose cadastre, which means that it supports the land administration functions of land tenure, value, use and development. Land tenure is about securing and transferring rights in land, but also in natural resources. Land value is concerning the valuation and taxation of land and properties. Land use deals with planning and controlling land use and the use of natural resources. Land development is about the planning of infrastructures and constructions and implementing utilities. The role of the cadastral map, which requires a large scale, is to show the boundaries of land parcels. Land information, such as the land rights of people, are able to be linked to the land parcels identified on the cadastral map with the use of a parcel identifier.

This MSc thesis is proposing the general boundary concept for determining the boundaries of land parcels. After examining the role of the cadastre and its cadastral map, objective two is to investigate how airborne laser scanning can be beneficial for deriving topographic features for the purpose of general boundary based cadastral mapping. Airborne laser scanning is capable of producing highly accurate x,y,z measurements in the form of a 3D point could dataset. The point clouds produced by airborne laser scanning can be converted to highly detailed DEM images, which match the earth's surface. Topographic features, which are visible due to height differences, can be detected from these point clouds. Airborne laser scanning provides several advantages: (1) light conditions are less critical for airborne laser scanning, (2) canopy penetration, (3) fast data acquisition and (4) providing high measurement density and high data accuracy. These advantages of airborne laser scanning are very beneficial for constructing cadastral maps with general boundaries in developing countries. There is an urgent need for cadastral maps, so fast data acquisition desirable. The fact that light conditions are less critical for airborne laser scanning, can accelerate the acquisition of data and thereby the construction of a cadastral map with general boundaries. Weather conditions will not cause any delay. Canopy penetration is a big advantage, when a cadastral map with general boundaries has to be constructed in areas with a lot of vegetation. Topographic features, which serve as general boundary may be hidden underneath the canopy of trees. Airborne laser scanning is able the capture data of the area underneath the canopy.

The third objective is to examine how often a cadastral boundary coincides with a particular topographic features. This is necessary to gain knowledge on which particular topographic feature has a high chance of being a cadastral boundary. When this particular topographic features are identified, it is known where to search for in a point cloud. Knowledge on how often a cadastral boundary coincides with a particular topographic features is gained, by overlaying the BGT with the Dutch cadastral map for a selected research area. The research area is a part of the municipality of Best (The Netherlands). It is examined that 90 percent of the cadastral boundaries coincides with a topographic feature. The cadastral boundaries do most often coincides with water sections, road sections and delimitation of courtyards.

The next step is to provide a recommendation on the most suitable point cloud density for deriving topographic features for the purpose of general boundary based cadastral mapping. It is necessary to investigate which particular point cloud density is suitable for deriving the topographic features which are probable general boundaries. The Nyquist-Shannon sampling theorem is used to theoretically define the most suitable point cloud density. According to the Nyquist-Shannon sampling theorem, the smallest dimension (i.e. the width, length or height) of a topographic object should be used to determine the most suitable point cloud density for detecting a particular topographic feature. The smallest dimension (i.e. the width, length or height) of a topographic object in a point cloud should be at least twice as the same topographic object in reality, in order to recognise that particular object. The smallest dimension (width, length or height) of a topographic object will determine whether a topographic object will be visible in a point cloud. Therefore lines will be harder to detect than for example planes, because lines have a small width. However, it should be noticed that the Nyquist-Shannon does not always stand firm. Very long and thin objects, such as power lines, are also recognisable in a point cloud. According to the Nyquist-Shannon sampling theorem, very long and thin objects, should not be visible in a point cloud due to their small width. However, they are actually recognisable in a point cloud. The sampling theorem is tested with the use of the AHN 2 dataset. First of all, topographic features in a point cloud with an average density of 15 points per meter^2 are detected. Subsequently, the same is done for point clouds with average densities of 10 points per meter^2 , 5 points per meter^2, 1 points per meter^2 and 0.5 points per meter^2. The point clouds with an average density of 1 points per meter^2 and 0.5 points per meter^2 are proved unsuitable for recognising topographic features. When a developing country wants to order an airborne laser scanning survey for the purpose of constructing a cadastral map with general boundaries, it is recommendable to firstly determine which kind of topographic features (which could serve as general boundary) have to be derived from airborne laser scanning data. Topographic features, of which one of the dimensions (width, length, height) is very small require a high point cloud density in order to be detected in and derived from a point cloud. An example is a fence, which has a small width. Photogrammetry would be a better data acquisition technique for recognising fences on a raster image. However, detecting and deriving topographic features with bigger dimensions (width, length, height) from airborne laser scanning is possible.

Objective 5 is to design a workflow for constructing a cadastral map with general boundaries with the use of topographic features derived from of airborne laser scanning data. Firstly, it is necessary to filter a point cloud in such a way, that a point cloud without high vegetation and a point cloud with solely ground points is obtained. A point cloud containing all the points, a point cloud without high vegetation and a point cloud with solely ground points have to be converted to 2.5D DEM images. A division is made in different point clouds, to provide 2.5D DEM images. Each different 2.5D DEM image, is suitable for detecting different topographic features (for example the 2.5D DEM image of ground points is suitable for detecting water and road sections). The 2.5D DEM images are obtained by, overlaying a DEM of the actual values and a hillside shaded DEM. The DEM of actual values should be made transparent. After the construction of the 2.5D DEM images, topographic features which are probable general boundaries can be detected and extracted. In this way, 2.5D DEM images with probable boundaries are constructed. These 2.5D DEM images with probable boundaries can be taken into the field for recordation. The boundaries of parcels have to be drawn on these images, with the use of a pencil or marker pen. Instructions of right holders in the field are necessary for this process. Subsequently, the 2.5D DEM images and the 2.5D DEM images with drawn boundaries (simulated data) have to be used to construct parcels in a GIS environment. This has to be performed by overlaying the images. This can be achieved by georeferencing the 2.5D DEM image with drawn boundaries to the 2.5D DEM image. Finally, the constructed parcels in the GIS environment are overlaid with the 2.5D DEM images and together they form the spatial framework for the cadastral map. The 2.5D DEM images, which are part of the spatial framework for the cadastral map, also show several topographic features (for example buildings), which can be used as reference point.

Objective 6 is to propose a cadastral map with general boundaries constructed with the use of topographic features derived from airborne laser scanning data. This is done by implementing the workflow for the selected research area (municipality of Best). AHN 2 will be used as test data. This research has not dealt with recordation in the field, but it simulated data is used. No instructions of right holders in the field are used for drawing the boundaries and parcels.

Airborne laser scanning is proved suitable for deriving topographic features for the purpose of general boundary based cadastral mapping. With the use of 2.5D DEM images, topographic features can be detected and extracted for the purpose of constructing a cadastral map with general boundaries. However, detecting and extracting particular topographic features depends on the point cloud density. Therefore, it is necessary to know on forehand which topographic features in a particular area of country will serve as general boundary. If this is known, the required point cloud density can be determined. Topographic features with a small width, length or height require a higher point cloud density in order to be detected and extracted, than topographic features with a large width, length or height. Ditches have for example a small width, when the point cloud density it is not sufficient, it will be hard to detect and extract them. It should be noticed that this theory does not always stand firm. Very long and thin topographic features, such as power lines, are also recognisable in a point cloud. Another condition for detecting and extracting topographic features with the use of airborne laser scanning, is that the topographic features needs to distinguish themselves based on their height characteristic. A road surrounded by flat grassland is for example hard to recognise, because the road does not distinguish itself from the grassland with the use of its height characteristic. However, when a road is surrounded by curbs, which have a different height, it is possible to detect the road.

9 DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

An item of discussion is the result of the overlay of the BGT and the Dutch cadastral map. The overlay is performed for a small rural area. The results will become more valid if the overlay will also be performed for a larger area. In this way, the amount of investigated cadastral boundaries will increase and therefore a better indication can be provided on the coincidence of cadastral boundaries and topographic features. It also advisable to overlay the BGT and the Dutch cadastral map for different types of areas, for example an urban area. An urban area will consist of other topographic features than a rural area and therefore cadastral boundaries in an urban area will (or will not) coincide with different topographic features. It should also be noticed, that the counting of the coincidence of cadastral boundaries and topographic objects is performed by hand. This is because the cadastral boundaries are loaded into a GIS environment with the use of a WMS, which does not allow automated analysis. The counting of coinciding cadastral boundaries and topographic features will become more valid, if this is done by computer. When the counting is done automatically by a computer, partial overlap will also be included.

The overlay of the BGT and the Dutch cadastral map is performed, in order to provide an indication on how often cadastral boundaries coincide with a topographic feature. It is also advisable to investigate how often a topographic feature coincides with a cadastral boundary. An indication for this can be provided, by determining all topographic features in a selected research area (or several research areas) and investigate how often they are a cadastral boundaries. In this way, a percentage can be given to a topographic feature, which is indicating the chance of that particular topographic feature to be a cadastral boundary.

Another topic of discussion is that the workflow for constructing a cadastral map with general boundaries with the use of airborne laser scanning is performed for a flat rural area. The workflow will become more valid, if the workflow will also be tested for an urban area, a forested area and other types of area. Testing the workflow for a forested area would be recommended, because one of the advantages of airborne laser scanning is canopy penetration. This also relates to the required point cloud density which is necessary to detect topographic features. This research has investigated the suitability of a particular point cloud density for detecting and extracting topographic features. However, it is not taken into account which point cloud density is necessary to detect topographic features underneath tree canopy. Only a part of the laser pulse of an airborne laser scanner will pass the tree canopy. Therefore, it is advisable to investigate which point cloud density is necessary to detect and extract topographic features underneath tree canopy. It should be noticed, that also the type of tree should be taken into account. Trees in a rainforest form a much denser canopy, than for example the trees in a deciduous forest.

Testing the workflow for an urban area would also be recommended. In developing countries, people are moving more often from rural areas to urban areas. This phenomena is called urbanisation. An urban area consist of many topographic features, which could potentially serve as general boundaries. In developing countries, cities contain for example often of an area with slums. These slums in big cities are demolished and subsequently flats are built on this terrain. The rights of the inhabitants of the slums are completely neglected. However, the small houses in slums can serve as general boundary and can be easily mapped with the use of airborne laser scanning.

During this research, the validation of the constructed map with general boundaries is based on a topographic map, namely the BGT. It is examined, that the boundaries which are constructed with the use of airborne laser scanning are often coinciding with topographic features. However, it is not mentioned how often they are coinciding with topographic features. In order to provide a better validation of the constructed map with general boundaries, it is advisable to perform further qualitative and quantitative analysis.

This research manually extracts topographic features from 2.5D DEM images constructed from point clouds. However, the process of constructing a cadastral map with general boundaries will accelerate if it is possible to automatically classify a point cloud. It is already possible to automatically classify points representing buildings, points representing high vegetation and ground points. It would be very beneficial if topographic objects, such as fences and stone walls, can automatically be classified in a point cloud. When this is possible topographic features could be extracted much faster.

Investigating the automated extraction of topographic features from DEM images is another option to speed up the construction of a cadastral map with general boundaries. Several software packages are able to automatically extract topographic features from raster images constructed with the use of airborne laser scanning data. Some experimenting with automated feature extraction from raster images is conducted during the research, however without the required results.

During this research, LAStools is used for point cloud filtering and converting point cloud into 2.5D DEM images. However, the quality of LAStools is not investigated. It is advisable to check whether the points of a point cloud are classified in the right way.

The detecting and extraction of topographic features from airborne laser scanning data will receive an impulse, if the airborne laser scanning data is supplied with RGB codes and intensity codes. It is advisable to investigate the possibilities of topographic feature extraction with the use of the RGB codes and intensity codes of an airborne laser scanning dataset. It would also be advisable to combine airborne laser scanning with other data acquisition techniques such as photogrammetry, in order to detect topographic features.

A suggestion to improve the “recordation in the field” part of the workflow, is to use tablets. This would speed up the process of drawing boundaries in the field. When a tablet could be used for drawing boundaries, it is unnecessary to print 2.5D DEM images, containing topographic features, on large papers of A0 format. The digitising of the obtained images with boundaries will also become unnecessary. The use of tablets will also provide more visual interactions and visual method, which can make topographic features (which coincide with general boundaries) visible.

Finally, it is recommended to investigate the costs of constructing a cadastral map with general boundaries from airborne laser scanning data. The costs should become as low as possible, because developing countries do not have a lot of money to spend. This research already paid a little attention to the suitable point cloud density for detecting and extracting topographic features. However, this research did not take into account the costs of data and software packages. During this research, ArcGIS and LAStools are used for the construction of a cadastral map with general boundaries. Both software packages require a license, which costs money. Therefore it is recommended to examine if the developed workflow for constructing a cadastral map with the use of airborne laser scanning also can be implemented with the use of open software packages.

REFERENCES

1. AHN (2014), Het AHN: Inwinning en productie. WWW site http://www.ahn.nl/pagina/het-ahn/inwinning-en-productie.html [accessed: 03-10-2014].

2. ArcGIS Help 10.1 (2012), Contour (Spatial Analyst). WWW site http://resources.arcgis.com/en/help/main/10.1/index.html#//009z000000ts000000 [accessed: 16-01-2015].

3. ArcGIS Help 10.1 (2014), Georeferencing tools. WWW site http://resources.arcgis.com/en/help/main/10.1/index.html#//009t000000mp000000 [accessed: 16-01-2015].

4. ArcGIS Help 10.2 (2013), A quick tour of editing. WWW site http://resources.arcgis.com/en/help/main/10.2/index.html#//01m500000002000000 [accessed: 16-01-2014].

5. Bell, K.C. (2006), World Bank support for land administration and management: responding to the challenges of the Millennium Development Goals. WWW site https://www.fig.net/pub/monthly_articles/november_2006/bell_november_2006l.pdf [accessed: 08-09-2014].

6. Bie, M. de, Creemers, G., Meylemans, E., Paesen, J. (2011). Laseraltimetrie en de kartering van Celtic Fields in de Belgische Kempen: mogelijkheden en toekomstperspectieven. Relicta 7, pp. 11 – 36.

7. Bogaerts, T. & Zevenbergen, J. (2001), Cadastral systems – alternatives. Computers, Environment and Urban Systems 25, pp. 325-337.

8. Crosilla, F., Triglac Cekada, M., Kosmatin Fras, M. (2010), Theoretical LiDAR point density for topographic mapping in the largest scales. Geodetski vestnik 54, pp. 403 – 416.

9. Dale, P.F. (1995), Cadastral surveys and records of rights in land. Rome: Food and agriculture organization of the United Nations.

10. Duncan, A., Jaafar, J., Priestnall, G. (2000), Extracting urban features from LiDAR digital surface models. Computers, Environment and Urban Systems 24, pp. 65 – 78.

11. Enemark, S. & Williamson, I. (1996), Understanding Cadastral Maps. The Australian Surveyor 41, pp. 38 – 52.

12. Enemark, S. (2005), Understanding the land management paradigm. WWW site http://vbn.aau.dk/ws/files/625999/SE_FIG_COM7_2005_Understanding.pdf [accessed: 09-09-2014].

13. Enemark, S., Wallace, J., Williamson, I. (2005), Building Modern Land Administration Systems in Developed Economies. Spatial Science 50 (2), pp. 51 – 68.

14. Enemark, S. (2009) Land administration systems: Managing rights, restrictions and responsibilities in land. WWW site http://www.fig.net/council/enemark_papers/2009/hyderabad_enemark_paper_feb_2009.pdf [accessed: 09-09-2014].

15. Enemark, S., Bell, K.C., Lemmen, C., McLaren, R. (2014), Fit-For-Purpose Land Administration. FIG Publication 60, pp. 1-41.

16. FIG commission 7 (1995), FIG Statement on the Cadastre. WWW site https://www.fig.net/commission7/reports/cadastre/statement_on_cadastre.html [accessed: 01-12-2014].

17. Geoshot (2015), LiDAR: Why do we need it? WWW site http://www.geoshott.com/details.php?post=lidar:-why-do-we-need-it?-.php [accessed: 14-02-2015].

18. Hall, R. (2011), Land grabbing in Southern Africa: the many faces of the investor rush. Review of African Political Economy 38 (128), pp. 193 – 214.

19. Henssen, J. (1995), Basic principles of the main cadastral systems in the world. Proceedings of the one day seminar held during the annual meeting of commission 7, cadastre and rural land management, of the International Federation of Surveyors (FIG), May 16, Delft, The Netherlands.

20. Heywood, I., Carver, S., Cornelius, S. (2011). An introduction to geographical information systems. Harlow: Pearson Education.

21. Huurneman, G.C., Janssen, L.L.F., Kerle, N., Tempfli, K. (2009), Principles of Remote sensing: An introductory textbook. Enschede, ITC.

22. ISO 19152 (2012), Geographic information – Land Administration Domain Model (LADM). WWW site https://www.iso.org/obp/ui/#iso:std:iso:19152:ed-1:v1:en [accessed: 26-02-2015].

23. Leakey, R. (1996), Definition of Agroforestry revisited. Agroforestry today 8, pp. 5 – 7.

24. Lemmen, C., Augustinus, C., Oosterom, P. van (2009), The Social Tenure Domain Model, a pro-poor land rights recording system. GIM International 23, pp. 40 – 45.

25. Lemmen, C. (2012), A Domain Model for Land Administration. PhD Thesis. TU Delft, The Netherlands, p. 244.

26. Lemmens, M. (2011), Geo-information: technologies, applications and the environment. Dordrecht, Heidelberg, Berlin, London, New York: Springer.

27. Maas, H.G. & Vosselman, G. (2010), Airborne and terrestrial laser scanning. Boca Raton: CRC.

28. Ministerie van Infrastructuur en Milieu (2013), Basisregistratie grootschalige topografie: Gegevenscatalogus BGT 1.1.1. WWW site http://www.geonovum.nl/sites/default/files/BGTGegevenscatalogus111.pdf [accessed: 12-11-2014].

29. Oosterom, P. van, Lemmen, C., Ingvarsson, T., Molen, P. van der, Ploeger, H., Quak, W., Stoter, J., Zevenbergen, J. (2006), The core cadastral domain model. Computer, Environment and Urban Systems 30, pp. 627 – 660.

30. Oosterom, P. van, Lemmen, C., Uitermark, H., Boekelo, G., Verkuijl, G. (2011), Land Administration Standardization with focus on Surveying and Spatial Representations. In: Proceedings of the ACMS Conference Survey Summit 2011, San Diego, p. 28.

31. OpenTopo (2014), Data repository AHN2. WWW site http://data.nlextract.nl/opentopo/ahn2/ [accessed: 10-11-2014].

32. Oxfam (2014), The G8 Summit – 2013. WWW site http://www.oxfam.ca/our-work/campaigns/g8-g20/northern-ireland-g8-2013 [accessed: 02-12-2014].

33. PDOK (2015), Home. WWW site https://www.pdok.nl/ [accessed: 01-02-2015].

34. Rapidlasso (2014a), lasboundary. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasboundary_README.txt [accessed: 24-10-2014].

35. Rapidlasso (2014b), lasclassify. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasclassify_README.txt [accessed: 24-10-2014].

36. Rapidlasso (2014c), lasground. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasground_README.txt [accessed: 24-10-2014].

37. Rapidlasso, (2014d), lasheight. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasheight_README.txt [accessed: 24-10-2014].

38. Rapidlasso (2014e), lasmerge. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasmerge_README.txt [accessed: 24-10-2014].

39. Rapidlasso (2014g), lassplit. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lassplit_README.txt [accessed: 24-10-2014].

40. Rapidlasso (2014f), lasthin. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/lasthin_README.txt [accessed: 24-10-2014].

41. Rapidlasso (2015a), blast2dem. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/blast2dem_README.txt [accessed: 24-01-2015].

42. Rapidlasso (2015b), las2dem. WWW site http://www.cs.unc.edu/~isenburg/lastools/download/las2dem_README.txt [accessed: 17-02-2015].

43. Rapidlasso (2015c), lasclip. WWW site https://www.cs.unc.edu/~isenburg/lastools/download/lasclip_README.txt [accessed: 17-02-2015].

44. Ting, L. & Williamson, I. (1999), Land administration and cadastral trends, the impact of the changing humankind-land relationship and major global drivers. WWW site https://www.fig.net/figun/sessions/session3/ting.pdf [accessed: 05-01-2015].

45. UN-ECE (1996), Land administration guidelines: with special reference to countries in transition. WWW site http://www.unece.org/fileadmin/DAM/hlm/documents/Publications/land.administration.guidelines.e.pdf [accessed: 08-09-2014].

46. UN-Habitat (2008), Secure land rights for all. WWW site https://www.responsibleagroinvestment.org/sites/responsibleagroinvestment.org/files/Secure%20land%20rights%20for%20all-UN%20HABITAT.pdf [accessed: 19-12-2014].

47. Uitermark, H., Oosterom, P. van, Zevenbergen, J., Lemmen, C. (2010), From LADM/STDM to a Spatially Enabled Society: a Vision for 2025. In: Proceedings of the Annual Bank Conference on Land Policy and Administration, April 2010, Washington D.C., pp. 1 -13.

48. Waterschapshuis (2012), Wat kan het AHN2 betekenen voor BGT? WWW site http://www.ahn.nl/binaries/content/assets/hwh---ahn/nieuws/2012/07/ahn_bgt_rapport.pdf [accessed: 03-11-2014].

49. Wikipedia (2015a), Agroforestry. WWW site http://en.wikipedia.org/wiki/Agroforestry [accessed: 08-02-2014].

50. Wikipedia (2015b), Zimbabwe. WWW site http://en.wikipedia.org/wiki/Zimbabwe [accessed: 14-02-2015].

51. Williamson, I., Enemark, S., Rajabifard, A., Wallace, J. (2010), Land Administration for Sustainable Development. Redlands: Esri Press.

Appendices

- Appendix 1: The topographic features of the BGT
- Appendix 2: Using different colour ramps for the visualisation of DEMs
- Appendix 3: Multiresolution segmentation and classifying in eCognition
- Appendix 4: LASboundary for extracting buildings and vegetation
- Appendix 5: Extracting topographic features with the use of contour lines

Appendix 1: The topographic features of the BGT

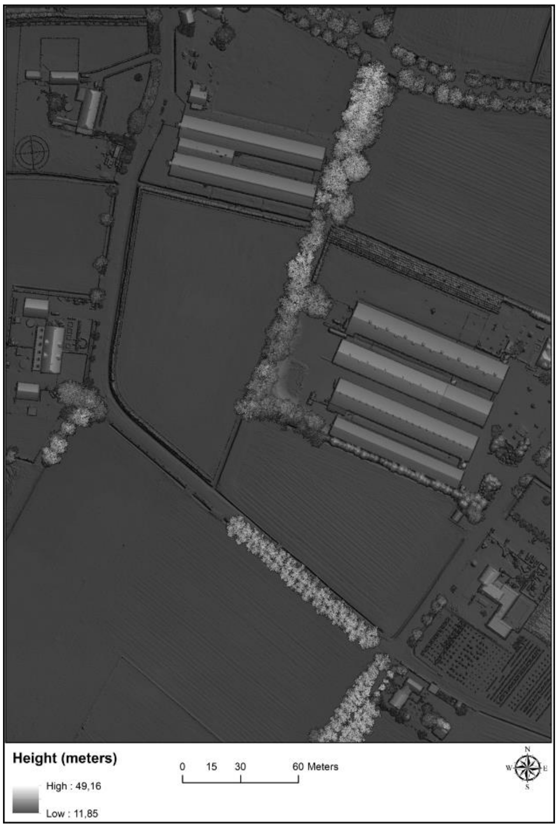
Table A1: Topographic features of the BGT (with a few adjustments)

<table>
<tr><th>Main group</th><th colspan="2">Sub group</th><th>Topographic features</th></tr>
<tr><td rowspan="3">Transport</td><td colspan="2">Road section</td><td>Public transport lane, railroad crossing, railway, air traffic lane, carriageway of a motorway, carriageway of a freeway, carriage way of a collector road, carriage way of a local road, cycle path, footpath, footpath on stairs, bridle path, parking space, pedestrian zone, driveway, home zone.</td></tr>
<tr><td colspan="2">Supportive (rail)road section</td><td>Traffic island, (rail)roadside</td></tr>
<tr><td colspan="2">Railroad section</td><td>Train, light rail, tram</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="2">Terrain</td><td colspan="2">Bare terrain</td><td>Courtyard, paved, unpaved, sand</td></tr>
<tr><td colspan="2">Covered terrain</td><td>Deciduous forest, mixed forest, coniferous forest, heathland, shrubs, wooded bank, dune, marsh, reed land, salt marsh, fruit-growing, tree cultivation, arable land, grassland agriculture, grassland other, green area.</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="2">Water</td><td colspan="2">Water section</td><td>Sea, watercourse, surface water, dry ditch.</td></tr>
<tr><td colspan="2">Supportive water section</td><td>Shore/side of a ditch, mire</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="6">Construction</td><td colspan="2">Building</td><td>Building</td></tr>
<tr><td colspan="2">Other construction</td><td>Covering, open shed, storage tank, clarifier, wind turbine, low transformer, basin.</td></tr>
<tr><td rowspan="3">Engineering structure</td><td>Bridging section</td><td rowspan="3">Bridge, tunnel, transmission tower, pumping station, railroad platform, sluice, breakwater, wharf, weir.</td></tr>
<tr><td>Tunnel section</td></tr>
<tr><td>Engineering structure section</td></tr>
<tr><td colspan="2">Partition</td><td>Wall, quay wall, dam wall, noise barrier, embankment protection, fence</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Unclassified object</td><td colspan="2">-</td><td>Unclassified object</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Functional area</td><td colspan="2">-</td><td>Barrier</td></tr>
</table>

Source: Ministerie van Infrastructuur en Milieu, 2013

Appendix 2: Using different colour ramps for the visualisation of 2.5D DEM images

Figure A1: Using different colour ramps of ArcMap: black to white (left image) and spectrum-full bright (right image)



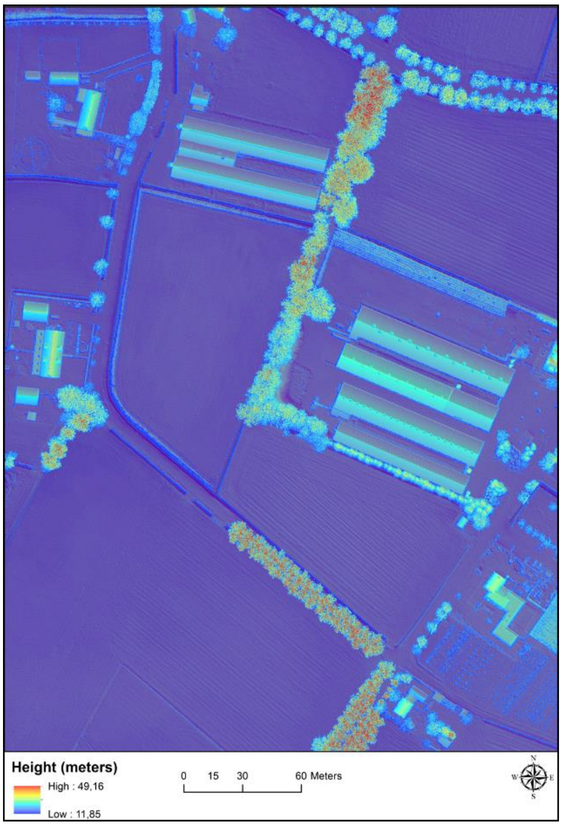
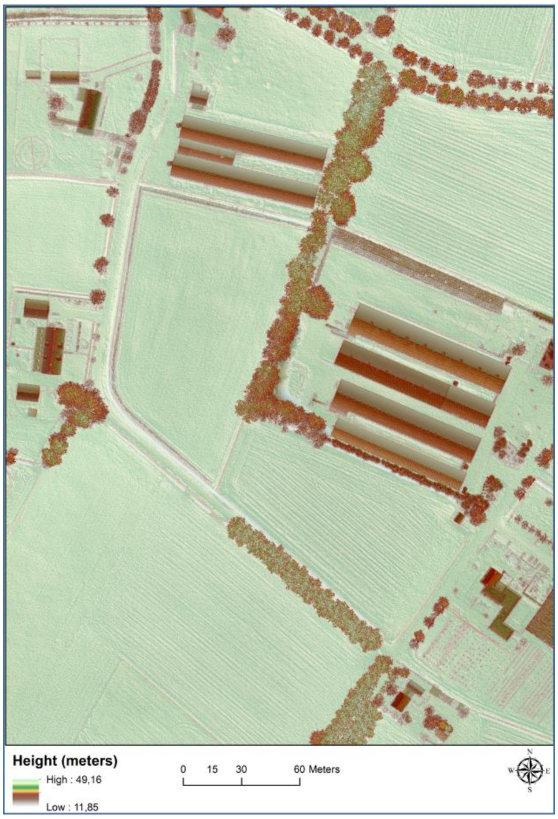


Figure A2: Using different colour ramps of ArcMap: elevation #1 (left image) and yellow to dark red (right image)



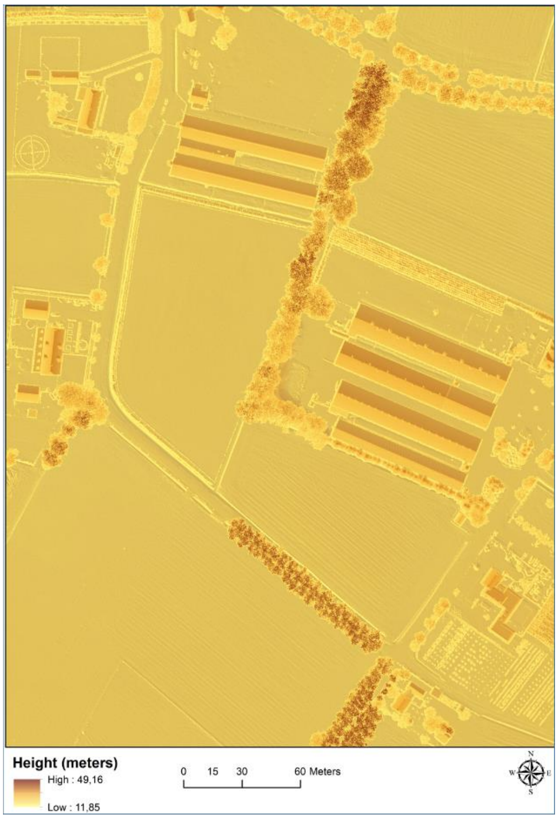
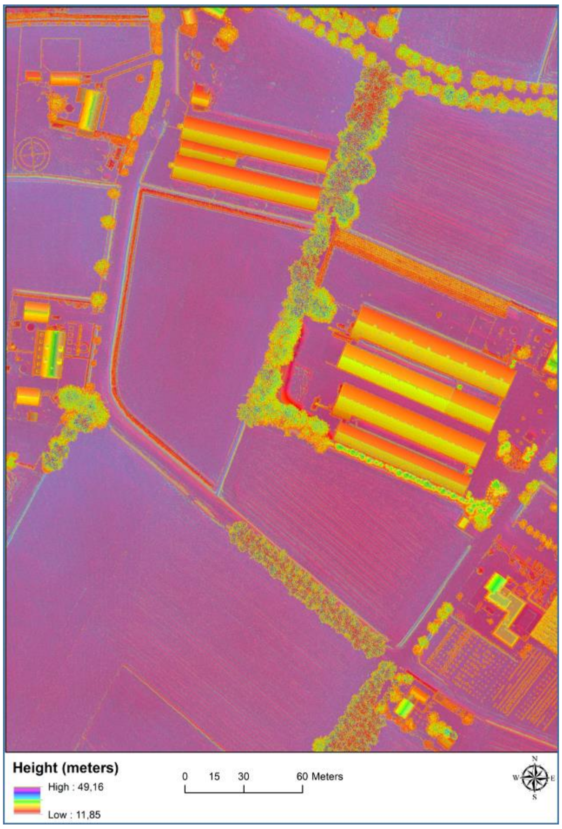
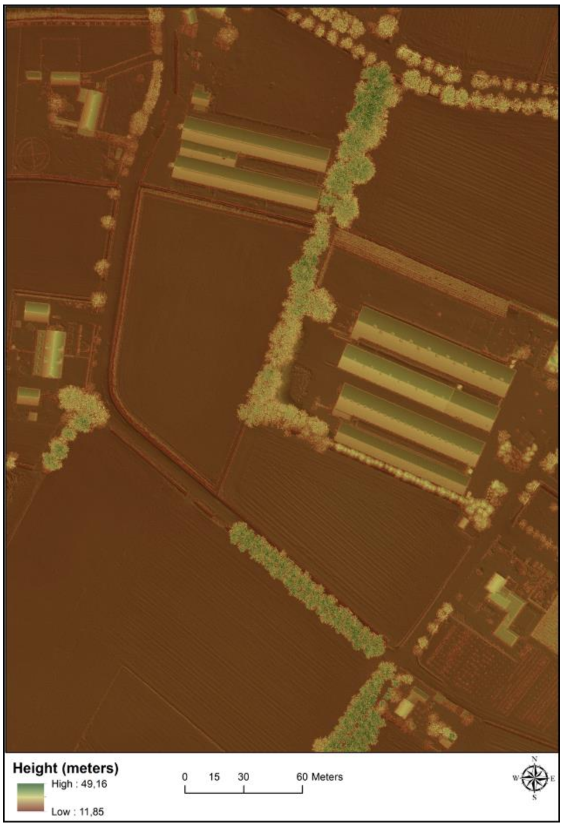


Figure A3: Using different colour ramps of ArcMap: aspect (left image) and red to green deverging, dark (right image)





Appendix 3: Multiresolution segmentation and classifying in eCognition

Figure A4, figure A5 and figure A6 are showing how to extract a ditch, a road and a building with the use of eCognition. First of all, multiresolution segmentation is performed. Multiresolution segmentation applies an optimization procedure which locally minimizes the average heterogeneity of image objects for a given resolution. In others words: the tool creates segments of pixels with almost the same height value. The problem with the multiresolution segmentation tool of eCognition is that the segments created by the tool, do not always fit the topographic which has to be extracted. For example: a part of agricultural grassland may belong to the segment of a shore or a ditch. In other words: it is always looking for the right parameters. Another disadvantage is that the process of selecting and merging segments belonging to a particular topographic object, requires a lot of time. In the future, further research is necessary for trained classifier which are able to detect particular topographic features automatically.

Figure A4: Extracting ditches with the use of eCognition. Image A: recognising a ditch. Image B: selecting the segments belonging to a ditch. Image C: merging the selected segments belonging to a ditch. Image D: A classified ditch.

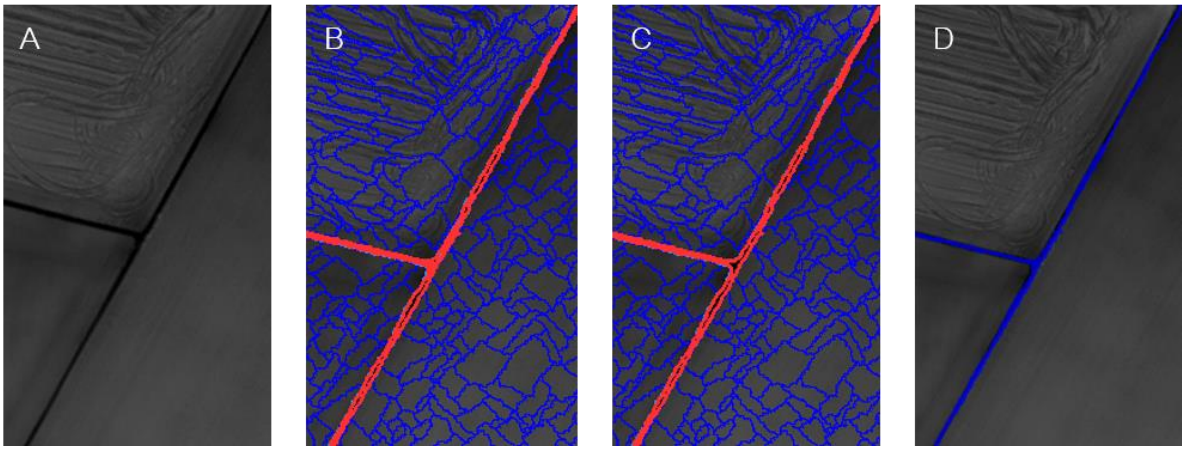


Figure A5: Extracting roads with the use of eCognition. Image A: recognising a road. Image B: selecting the segments belonging to a road. Image C: merging the selected segments belonging to a road. Image D: A classified road.

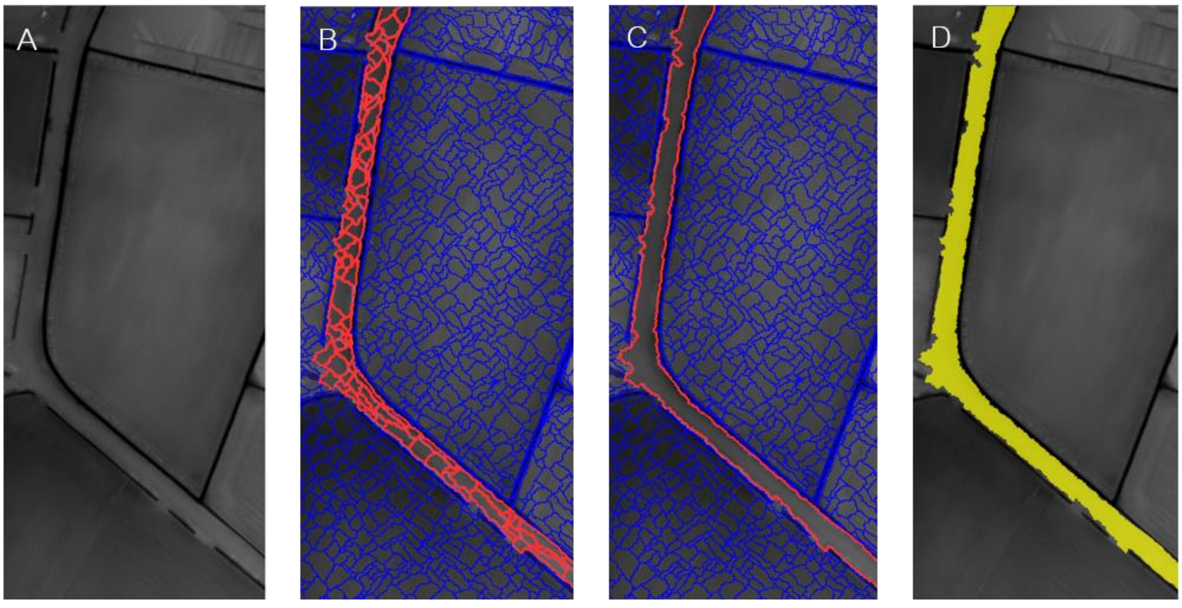
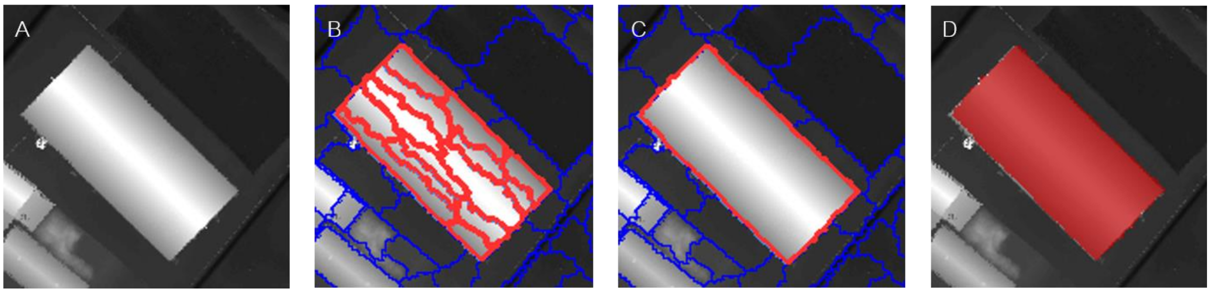


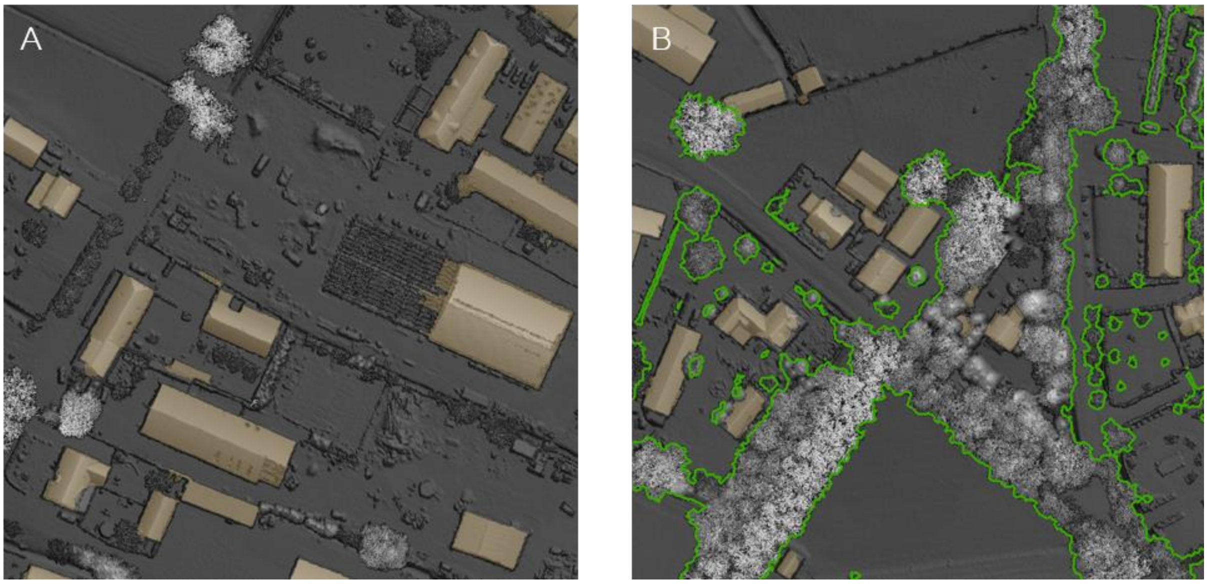
Figure A6: Extracting a building with the use of eCognition. Image A: recognising a building. Image B: selecting the segments belonging to a building. Image C: merging the selected segments belonging to a building. Image D: A classified building.



Appendix 4: LASboundary for extracting buildings and vegetation

Figure A7 is showing buildings and vegetation which are extracted, with the use of LASboundary. LASboundary reads laser scanning data and computes a boundary polygon for the classified points (Rapidlasso, 2014a). Image A of figure A7 is showing extracted buildings. Several extracted building polygons do fit the buildings, which can be recognised on the 2.5D DSM image. However, some of the extracted building polygons do not represent a building, but another topographic feature. Image B of figure A7 is showing extracted vegetation. When there are “holes” in a group of tree, LASboundary still sees the “hole” as a tree. This is wrong. It is always searching for the right parameters, to extract topographic features as good as possible.

Figure A7: Extracting buildings (image A) and extracting vegetation (image B) with the use of LASboundary



Appendix 5: Extracting topographic features with the use of contour lines

Figure A8 is showing a 2.5D DTM image with contour lines. The contour lines are constructed with the use of the “contour tool” of the spatial analyst toolbox of ArcGIS. The tool is able to create a line feature class of contours (isolines) from a raster surface, in this case a 2.5D DTM image (ArcGIS Help 10.1, 2012). The tool is able to detect some topographic features, for example ditches. However, not each ditch is extracted. This is related to searching for the right parameters, to extract topographic features as good as possible.

Figure A8: Extracting topographic features with the use of contour lines