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Low budget ranging for forest management

A Microsoft Kinect study

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Abstract

Recent advancements in forestry science provide foresters with technology to accurately measure and analyze tree metric data within almost any forest stand. Ranging technology and other advancements in the field of remote sensing have increased the efficiency from measuring individual trees significantly in the last decade. However small scale foresters are having trouble keeping up with the efficiency from large forestry companies using the expensive ranging technology such as LiDAR to make the lowest cost production ratio possible.

A smaller less expensive device that could still acquire accurate tree metric data would benefit small scale foresters to compete larger forestry companies. Light Coding, which is used within devices such as the Microsoft Kinect, can be used to collect data which could be useful in forestry assessments and decision making software.

Forestry data was obtained from different forest stands near Wageningen, the Netherlands. Two production forest stands and two mixed heterogeneous forest stands were measured. The data obtained was subjected to numerous calibrations and modifications for optimization. It was proven that Microsoft Kinect data can be used in forestry applications. Tree metric data was able to be extracted in coniferous, deciduous, shrub and mixed forest stands. However the Microsoft Kinect has limitations, mixed and shrub forest stands are difficult to distinguish and higher light ranging resolution is needed for better extraction.

A forestry assessment decision making model was created to test the both Microsoft Kinect and LiDAR data. This model was based upon growth factors and other forest principles. Forestry data obtained in production stands was used in decision making software to produce forest management schemes for deciduous and coniferous species. Nevertheless, tree metric data obtained by the Microsoft Kinect has proven to be useful for the automatization of forestry assessment.

The evaluation of the data proved that data within standard forestry settings could be used for forestry assessments. LiDAR data was compared with Kinect data and for production stands had roughly the same result for both stand as tree characteristics. The manual assessment proved that the Microsoft Kinect data within the decision making software can make decisions as accurately and precise as expert forestry assessments.

Keywords: Microsoft Kinect, precision forestry, ranging applications, forestry modeling, tree metrics, forestry assessment, decision science, remote sensing, structured light coding.

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Finally I would like to thank my parents, my brother Jeroen, and my girlfriend Jarinka Heijink for without them this world would be an empty place.

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List of Abbreviations

2D	2 Dimensional
3D	3 Dimensional
BSD	Berkeley Software Distribution
DBH	Diameter Breast Height
GIS	Geographic Information Systems
GPS	Global Positioning System
FSC	Forest Stewardship Council
FOV	Field Of View
IR	Infrared
LiDAR	Light Detection And Ranging
LBG	Liquefied Bio Gas
MFA	Manual Forestry Assessment
TLS	Terrestrial Laser Scanner
OS	Operating System
PC	Personal Computer
PCL	Point Cloud Library
RGB	Red Green Blue
ROS	Robot Operating System
USB	Universal Serial Bus

Chapter 1. Introduction

1.1 Motivation

Foresters today are faced with a competitive global product market. It's becoming more difficult for small scale foresters to provide competition against larger automated forest plantations (Nair, 2007; Zhang *et al.* 2005). Where large forest plantations are automated with expensive supportive machinery and software, small scale foresters, not able to finance expensive forestry equipment, tend to fight back with dynamic forest management schemes and product quality.

Precision forestry provides new opportunities to support small scale foresters in assessing and monitoring forest stands accurately for ecological and economical elements. In recent years, remote sensing has developed itself as the backbone of precision forestry (Hamzah, 2011). Because forestry is highly depending upon the accurate monitoring of specific forest characteristics, recent developments such as the creation of a vegetation indexes for LiDAR data or increased specie identification from aerial LiDAR data (Moskal *et al.* 2009), in the field of remote sensing have benefitted the speed, precision and accuracy of these measurements. In forestry, remote sensing applications can be used as a decision making tool in procedures such as biomass monitoring and health management (Lim *et al.* 2003).

Aerial and terrestrial LiDAR, *Light Detection and Ranging, as well as other ranging applications* has been proven to be helpful in analyzing forest stands, such as stand value estimation (Murphy, 2008) and ecological surveys (Lefsky *et al.* 2002). Although aerial remote sensing data might be too crude for the subtle art of forestry (Holmgren and Thuresson, 2008), researchers in terrestrial LiDAR applications have developed methods for monitoring stem and branch structure, which are an indicator for log quality (Briggs *et al.* 2008), stem volume and stand characterization (Moskal *et al.* 2009).

The development of ranging applications in recent years increased in point density and accuracy of the procedures acquired (Latifi *et al.* 2010), while LiDAR instruments became more cost efficient, opening up the market for a wider audience. In recent years, forestry models were developed to support LiDAR data. These 3D terrestrial forestry measurements are integrated in forestry models to evaluate and predict forest stands. Forestry tools can support foresters with predicting future growth in biomass and tree height. Commercial institutes produced a number of products offering terrestrial LiDAR models to increase forestry productivity. These models can be used as a supporting decision tool in order to select potential dominant trees and thinning trees. Dominant trees are selected for their potential in economic revenue in the final harvest while thinning trees are selected to be cut for production (Tree Metrics, 2012).

Developments in small scale and low budget ranging applications, such as Primesense Light Coding™ technology, have been able to gain significant results. An example of such a low cost ranging sensor is the Microsoft Kinect, a videogame input device design within the Xbox system. This includes an infrared camera designed to track body position and movement at a single-articulation level. It can provide users with RGB, IR and depth measurements (Openkinect, 2012). The Microsoft Kinect was primarily designed for interaction in a video game environment

(Leyvand and tommer, 2011). However, Henry *et al. (2010)* showed the ability of the device in various scientific fields.

Currently, forest assessments are done almost entirely on the ground by field teams. Monitoring data is acquired on structure stands and specie characteristics and hereafter is manually identified in GIS environments. Inventories are constructed within fixed weight area plots depending on local forestry policy or certification. These procedures take considerable time and money and are susceptible to subjective errors for each produce period. Ranging options such as LiDAR, especially terrestrial ranging options, are believed to significantly reduce the costs and energy within field work while increasing the precision and accuracy of forestry assessments. However, small scale foresters cannot finance expensive ranging equipment. This states the question if low budget scanning devices such as the Microsoft Kinect, can monitor and gain inventory automatically, reducing procedure time and money.

1.2 Research identification

1.2.1 Research objectives

The aim of this research was to obtain knowledge in acquirement of tree metrics in precision forestry with the Microsoft Kinect and its ability to function as a forestry tool in decision making processes. The research focuses on developing a procedure that distinguishes forestry characteristics which could be used in forestry decision making software, as well as an evaluation between the different ranging instruments and a manual forestry assessment. To accomplish this, three sub-objectives were constructed.

1. **Microsoft Kinect abilities for tree metric acquisition**

Can the Microsoft Kinect be used to determine different tree metrics in different forest stands? What are the possibilities and disadvantages of using the Microsoft Kinect in obtaining tree metric data? Here we research whether the Microsoft Kinect has the ability to acquire data, outside, in the field. Furthermore this data will be tested for the extraction of tree metric data. Ultimately, forest characteristics such as tree position, diameter on DBH and ultimately biomass will be presented as result.

2. **Microsoft Kinect abilities in precision forestry**

Can the existing static forestry models be converted to a dynamic forestry model in ArcGIS 10.0 and can this model be fed with low budget ranging Microsoft Kinect data? This will research the ability of Microsoft Kinect data to be fed into a dynamic forestry model, created in ArcGIS 10.0. The dynamic model will also be fed with RIEGL data in order to be compared with the acquired Kinect data.

3. **Microsoft Kinect abilities; quality assessment and evaluation**

Understand the differences in tree metrics acquisition and monitoring between low budget solutions such as the Microsoft Kinect (1) versus LiDAR systems such as the RIEGL (2) or the assessments of forestry specialist (3)? This will establish a comparison between three different forestry acquirement schemes.

1.2.5 Innovations

Terrestrial LiDAR options can provide forestry companies and foresters with excellent tree metric data. In combination with forestry models, they form the basis for an automatized forestry acquisition. Low budget ranging options can provide an interesting perspective for small scale foresters. Increasing the use of these scanners can increase the automatization of small scale forestry. At the same time, research can increase the abilities of low budget ranging scanning devices. In this study the Microsoft Kinect was tested on its abilities to measure tree metric data, in order to analyze these data in a forestry model. The innovation of this research is therefore mainly the applications of Microsoft Kinect in forestry including;

1. The ability to develop a procedure and measure stable tree metric parameters;
2. The use of Microsoft Kinect data and the ability of this data to be fed in forestry decision models.

1.2.6 Limitations

Because the scope of this project was proposed very narrowly, a number of limitations were instigated. Only large structural elements are being researched. This means smaller elements such as branches and upwelling root systems are not in the scope of this project, the same goes for individual species characterization. However, a division is made between deciduous, coniferous, mixed and shrub forest stands.

1.2.7 Thesis structure

This thesis is organized in a number of chapters. First of all, the introduction will contain a motivation, research identifications, innovation and limitations. Henceforward, the literature review will contain an exploratory research of the already established knowledge in forestry and remote sensing. The area characteristics will introduce the reader to the geographical and temporal settings.

The methodology will elaborate on the experiments overview. Additionally in the experiment setup, the devices and sampling design will be explained. The operational part clarifies the preprocessing, calibration and data correction, while the computation will discuss the data analysis. In forestry modeling, the modeling process will be clarified. Finally, this research report will end in a discussion, conclusion and a few recommendations for future research.

Chapter 2. Theoretical framework

The art of forestry is a very ancient one. The days where foresters pick up an axe and go into the forest to chop down any arbitrary tree are long gone. Nowadays, forestry companies have automatized the forestry industry beyond the point that every tree is planted, grown and cut down on a management scheme supported by algorithms and models. The art has been transformed into an industry. In recent years, remote sensing has become an important part of the forestry industry. This theoretical framework will explain some of the principles of the forestry and remote sensing used in the forestry industry.

2.1 Remote sensing principles

Remote sensing is defined as the measurement of object properties over a distance (Schowengerdt, 2006). It offers a broad variety of possibilities from satellite image interpretation to LiDAR analysis.

2.1.1 LiDAR and ranging measurements

LiDAR and other ranging measurements are a relatively new remote sensing technique, which uses light as measurement purpose. It measures the distance to an object in space by illuminating the object with a laser light and analyzing the backscatter light (Lefsky, 2002). The basic measurement made by any LiDAR application is the distance between the LiDAR sensor and an object, obtained by determining the elapsed time between the emission of a short duration pulse and the arrival of the reflection of that pulse at the sensor's receiver. Multiplying this time interval by the speed of light results in a measurement of the distance traveled, which divided by 2 results in the distance between the sensor and the target (Lefsky, 2002; Bachman 1979). LiDAR data in forestry is originally measured from aerial perspective, however in recent years terrestrial LiDAR has gained a more prominent role.

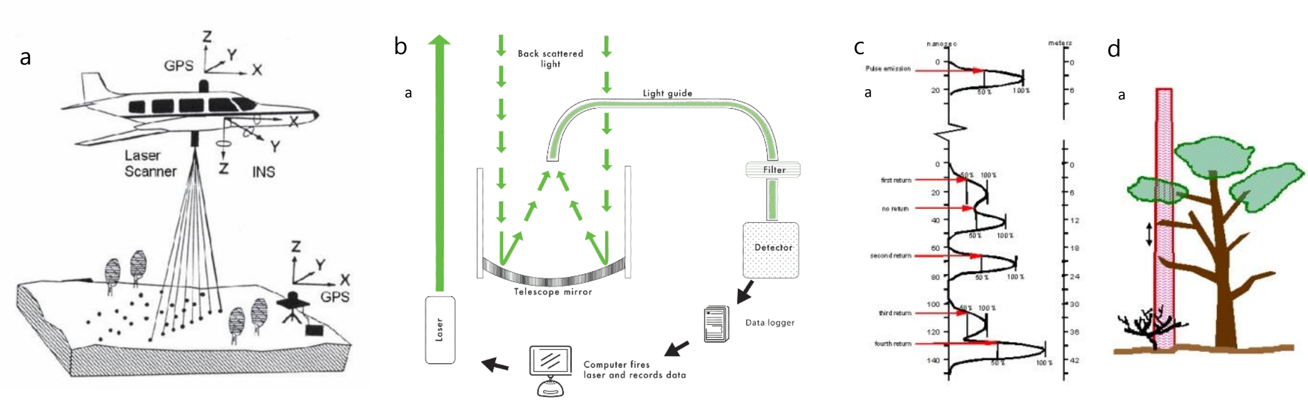


Figure 1; LiDAR Principles

The figures are depicting typical aerial LiDAR research in forestry. Where a beam of light is send out on the airplane, which subsequently receives backscatter light. This backscatter light is analyzed and digitalized. Hereafter the analysis of forest can be achieved by analyzing spectral signature of the backscatter.

Despite the advantages of using LiDAR in remote sensing applications, there are also some drawbacks. Water surfaces, including objects with water on top, will cause missing data or very low point data accumulation. This includes surfaces covered with snow. Another disadvantage is that point measurements cannot penetrate solid structures (Lillesand *et al.* 2004).

From the early 1980's the Canadian forestry service has demonstrated that LiDAR is proven useful in estimation of stands and beneath ground height, crown cover density (Aldred and bonner, 1985). Forestry applications in LiDAR really proved their weight in large forestry areas like the tropical forest of Central America (Arp *et al.*, 1982). Over time LiDAR scans have been further developed to measure alternative attributes in forestry. These attributes can be used in empirical models for even more advanced parameter extraction such as above ground biomass, mean stem diameter and canopy volume (Lefsky *et al* 1999).

In recent years, terrestrial LiDAR applications have proven their weight among forestry measuring tools (Popescu *et al*, 2003; Popescu and wynne, 2004). Terrestrial LiDAR differs from aerial LiDAR in point of measurement. Instead of measuring as a moving object, a scan is made on a stable position close to the ground. Terrestrial LiDAR scans are therefore more detailed, which causes terrestrial forestry data to be used in accurate forestry decision making models (Moskal, 2009). This research used the terrestrial laser RIEGL VZ 400.

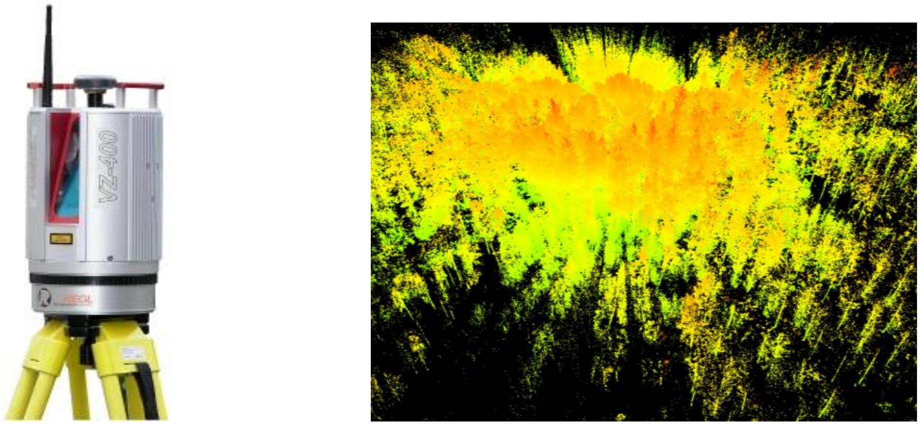


Figure 2, Terrestrial LiDAR

2.2.3 Structured light 3D scanner

Range scanning applications has evolved a substantial extent in recent years. Bernardini and rushmeier, 2000 as well as Curless and seitz, 2000 describe how ranging scanner developed from low tech photogram analysis towards an advanced 3D light scanning technology. Structured light scanning devices measures 3D patterns by using projected light patterns and a camera. Projecting a series of bands or points, as showed in figure 8, onto a 3D shaped surface, produces a pattern that appears distorted from other perspectives than that of the projector. After geometric reconstruction, this analysis can be used to derive the surface shape (Rocchinni *et al.* 2001). Identical as for LiDAR, structured light 3D scanners have limitations when projected on transparent or reflective surfaces such as snow, rain or water (Kutulakos and steger. 2005).

Structured light scanners have found a variety of applications in recent years. One of the most promising is the use of this technology in video gaming devices, one of the most popular being the Microsoft Kinect (Microsoft, 2013).

2.1.2 Microsoft Kinect

Besides a gaming device, after the launch of the Microsoft Kinect (previously known as project Nathal) in November 2010, the Kinect has proven to be a valuable device for 3D modeling and image acquisition. The Kinect has further proven to be a useful tool to scan and map the environment with a very detailed method. The Microsoft Kinect consists out of a RBG sensor with a 24-bit color sensor. The depth sensor is composed of an IR emitter projecting structured light, which is captured by the CMOS image sensor and decoded to produce depth measurements (Ramos, 2011; Villaroman *et al*, 2011)

The Kinect is based on a sensor design developed by PrimeSense Ltd (PrimeSense, 2013) which uses Light Coding™ technology, a form of structured light 3D scanning. It allows users to construct 3D depth plots of an object in real-time. Structured near-infrared light is cast on a surface and the CMOS image sensor is used to receive the reflected light. The PS1080 SoC (System on a Chip) is able to regulate the structured light with the aid of a light diffuser and is able to process the data from the image sensor to provide real time depth data (Villaroman *et al*, 2011).

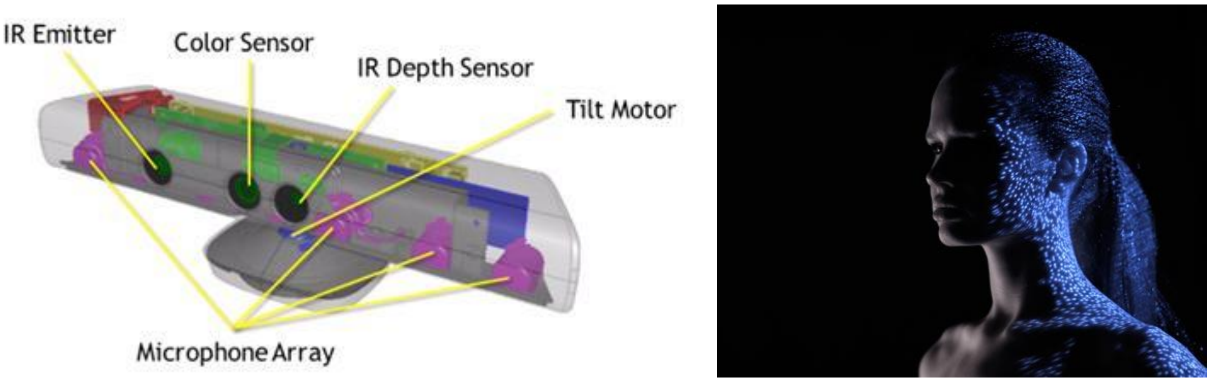


Figure 3 Kinect Properties

After the launch of the Microsoft Kinect in on November 9 2010, a race fueled by a commercial institute called Adafruit Industries (Adafruit, 2013), started among technicians and computer scientist to be able to interpret the Microsoft Kinects sensors in order to receive data on other platforms. By reverse engineering the Kinect and gaining access to its sensors, a new world of possibilities opened up (Giles, 2010).

2.2 Forestry principles

Recently, the overlap between forestry and remote sensing techniques has increased. Although forestry assessments will always be one of the most important decision tools in forestry, the method on which forestry is assessed will always be in development.

A small scale forester is usually affiliated with a larger forestry certifier. This ensures quality wood and forest products on the side of the consumer and a steady sale of wood product for the forester. For each of the forestry plots the forester creates a management scheme, where from seedling to clear cut, the entire life of the plot is planned. After a number of years, the management scheme is adapted to the specific trees, in order to maximize yield and ensure quality wood. This process repeats itself after a number of years, adapting to new situations. This ensures a dynamic management scheme in which wood production is optimized. The certifier overviews at a certain point in time, the management scheme and ensures the sustainability off which the certifier stands for. (Kruedener, 2000; Pattberg, 2006).

Forestry assessments are needed to maintain control of the harvest in forestry patches. In certified assessments such as that of the Forest Stewardship Council (FSC) (FSC, 2013), one off the larger wood and wood product certifiers, the forest is quantified on a number of criteria such as sustainability of the forest, environmental damage and climate change impact. In order to maintain a sustainable forest management it is therefore needed to analyze the forest structure and come up with a management plan of harvest and maintaining the forest (FSC 2, 2013).

2.2.1 Forestry management

Over time a large number of silviculture methods have been developed to maintain a sustainable forest. Older production forests are characterized by systematic tree schematics in which a solid distance between each tree is maintained. Modern sustainable forests differ in the dynamicity of the distance between trees and replace the systematic scheme by a more chaotic scheme in order to produce multiple species inside a single plot. Each forest is developed to have a specific outcome at the final stage of the forestry cycle. Each of these silviculture methods is therefore meant for different types of forests. In figure 7 it is depicted how different silviculture methods result in different forest types (Ecopedia, 2013). Most of these methods distinguish themselves in the different thinning methods used. Low thinning characterizes itself as a thinning method in which low quality trees, such as death, malformed or small trees are cut off, to create room for the dominant trees with economic potential. The high thinning method on the other hand removes the dominant trees to create room for co dominant and smaller trees (Nyland, 1996; Graham *et al.* 1999). A more recently developed method is called ecological thinning, in which the forest are thinned with consideration of ecological principles (Czembor and vesk, 2009), resulting in so called mixed forest types.

In recent years, precision forestry became a more popular method in forestry management. Precision forestry leverages advanced technology such as LiDAR and ranging devices, to support sustainable decision making incorporating ecological, social and economic elements of forestry (Farnum, 2001).

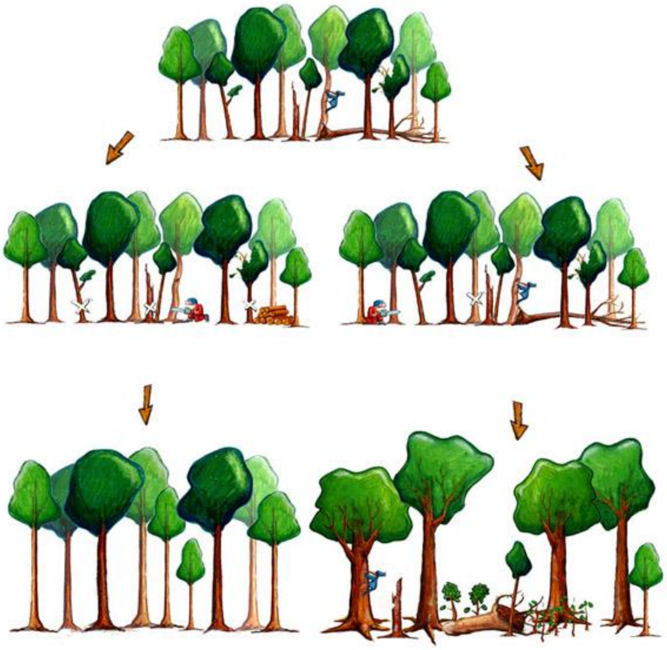


Figure 4. Two methods of forest management

2.2.2. Forestry measurement

Forests are measured using a variety of different standards and instruments. The heterogeneity of types of trees causes foresters to adapt their current methods for newly developed techniques. Therefor foresters created parameters equal for all trees. DBH, or Diameter at Breast Height, is one of these parameters, it measures the diameter at 1,30 meters above ground. Forestry measurement in the past, were done using a manual forest assessment. Foresters and certifiers used on the ground devices, such as measuring tapes and Blume leiss for data extraction (Den ouden *et al.* 2011). As mentioned, remote sensing and ranging devices have gained a more prominent role in forestry. This caused a few issues adapting from manual forestry assessments.

First of all, data extraction devices should be standardized on numerous tree species. Each tree species has a different structure and density, creating difficulties for standardized data extraction. In heterogeneous forest, data extraction becomes even harder, because forestry devices and models need to identify the tree species to be able to extract forestry data.

Forestry devices should also be able to work in field conditions within remote areas without any electricity or GPS coverage. Fleck *et al.,* 2007 suggested that because of the size of terrestrial laser scanner heterogeneous mixed forest with lot of diversity is hard to measure. Therefore a smaller more lightweight device such as a structured light scanner could provide a better solution. Thus forestry measuring devices should be small, effective and able to be used in a field environment. On the other hand the devices should be highly adaptive, and be able to measure through dense forest structure. The models analyzing forestry data should be adaptive as well.

2.2.3 Forestry modeling

Growth factors and yield tables are used in forestry to predict future forest stands and calculate future biomass. With the help of these instruments, foresters can predict their future biomass and with that, their economic revenue (Zeide, 1978). However in recent times, yield tables are replaced by ecological and forestry models, which are often much faster and yield more efficient results.

Forest and tree growth models, predict yield and biomass from target forest stands using side characteristics as input variables which result in a decision making model. Most of these tree models can be divided into three categories; whole stand model (1), size class models (2) and individual models (3) (Davis *et al* 2001). In forestry management usually whole stand models are used for decision making tools because individual and size class models increase the amount of input data and complexity from the model. Dynamic models can provide an option to increase complexity while decreasing the risk of overparameteralisation (Davis *et al* 2001).

Forestry model use a large number of parameters and calculations to support the decision making model. They can be based upon various parameters, from groundwater level till carbon sequestration. The simplicity of the model depends on the requirements of the outcome for the model by the user. Therefore, the personality of the data should be characterized by the choices made in the model.

A large number of forestry models have been conceived in the past few decades, the models differ in complexity, method and approach of calculating the most realistic tree growth values. I-Tree is a forestry model created by the USDA forest service and uses growth factors as basis for their tree growth algorithm. While other model like the Lindenmayer system use a more complex mathematical approach. Growth factors can be beneficial for simplistic growth model. (McPhearson and pepper, 2012). The International Society of Arboriculture (MDOC, 2013) and the Forestry Commission of the UK, has produced a list of these growth factors (White, 1998).

Chapter 3. Area characteristics

3.1 Location

The study area is located at the northeast side of Wageningen, The Netherlands, where it is part of a larger nature area called the Oostereng (51°59'N, 5°43'E)(van der Werf *et al.* 2007). The site originally was part of an experimental (nuclear) seed testing facility, now part of ministry of economic affairs, agriculture and innovation which later on was passed over to Staatsbosbeheer in the care of students from Wageningen University. The study area contains a number of different forest stands with different species and density characteristics. Additionally an arboretum is present. Four different areas were selected which represent four different types of forest stands.

Figure 5. Geographical location of Oostereng in Wageningen, The Netherlands

3.2 Stand characteristics

In the Oostereng four plots were selected, representing two production forest (deciduous and coniferous) and two mixed forest stands (mixed and shrub). The different forest stands were chosen for the variety in stand characteristics. The production forests were chosen because of their systematic nature, while the mixed forest stands were chosen for their species richness and high density. Beside a difference in species between the production forests stands, the plots had also a different stage of growth. The same goes for the mixed forest stands.

3.2.1 Deciduous forest stand

Deciduous forest stands are characterized by their ability to shed leafs during winter. Most deciduous forest in the Netherlands consists out of beech (*Fagus sylvatica*), oak (*Quercus robur)* and birch (*Betula pendula*) trees. Oak forest stands in the Netherlands are characterized by wide open forest stands without many additional species. This climax ecosystem is being created by a thick layer of humus and dead foliage which acidifies the understory causing a beech monopoly in older forest stands (Den ouden *et al*, 2010). Especially old forest stands of more than 100 years are very valuable in wood production.

A combination of oak and birch trees can be found in the Oostereng. Were the oaks were planted in a plantation setting. A setting was chosen for this research, of a small oak stand of approximately 20 years old. Because the oak trees are more interesting for wood production, the main deciduous forest study area will consist out of a monotonous oak forest stand with some birch trees in between. The oak trees were planted in rows off about a meter in distance. This stand is characterizes by very small stems with a closed canopy at a height of around 2 to 2,5 meters. This stand will represent the basic traditional production forest with deciduous species.

3.2.2 Coniferous forest stands

Coniferous species are characterized by all year round green species. The coniferous forest stands in this research are a monotonous stand of Douglas fir (*Pseudotsuga menziesii.)*. This nonnative species is mainly grown for wood production and is one of the most used trees in the Netherlands (Den ouden *et al*, 2010). The density of Douglas fir stands decrease when the stands increase in age. Although Douglas fir is a non-native species to the Netherlands, originating in Western North America, it has shown its ability as an effective production tree in Europe.

In the Oostereng a setting was chosen, of old Douglas fir approximate 50 years of age. The Douglas fir was planted in a typical production setting without any other species in between and approximately 2 meters of distance between the trees. The shape of these types of trees also differs from the deciduous trees and requires therefore a different acquisition approach.

3.2.3 Mixed forest stands

With the introduction of new forestry techniques the idea of a mixed forest with different species, coniferous as well as deciduous species became more popular. Mixed forest stands contain a number of different species and have usually a higher density than other production forests. This is causing the forests stands to use place more efficient and have a higher overall yield and therefore be more sustainable. Mixed forest stands are more difficult to be measured because of the higher density.

In the Oostereng a stand is selected containing diversity of species from all ages. Species of the Lark family are most prominent, but also *Betula spp.* and young fir and spruce species can be found. The trees varied in age, height, volume and structure.

3.2.4 Shrub forest stands

Shrub forest stands are normally smaller production stands which have a very young age. Because the growth of these types of trees are irregular, the trees differ from height and size. Measuring shrub species for wood production is a challenge. Because of the density of foliage and density of the species inside the stands are harder to measure.

The Oostereng contains a number of different stands which include shrub species as well as young upcoming tree species in mixed stands. A setting of small spruce was selected as plot. These 30 to 40 spruces varied in height from approximately 1 to 3 meters. The trees varied in height, volume and structure.

3.3 Temporal characteristics

The majority of the research was performed in the winter of 2012-2013. Kinect calibration was done early November 2012 and the actual research data was collected in the beginning of December 2012. The manual assessment was performed in early January and the RIEGL evaluation data was obtained in February. The weather conditions were mostly dry and slightly cloudy during most of the data acquirement. The RIEGL data was obtained in snow conditions.

Chapter 4. Methodology

This research could be divided in four parts, the preprocessing and data extraction, data analysis, the forestry modeling and evaluation. This study determines a number of tree metrics in four types of forest stands; deciduous, coniferous, mixed and shrub. The preprocessing step in this research includes the calibration of the Microsoft Kinect, inside and outside. Hereafter the data will be extracted in the field and this data will be subjected to noise removal software. Finally, the data will be exported to other software bundles and therefore (manually) transformed to other file types.

Hereafter, in data analysis, the data will be analyzed and tree metrics will be extracted, the initial parameters will be extracted from the data analysis, while the secondary parameters will be calculated from the initial parameters. Tree metric data contain tree characteristics such as DBH, while health derivatives give an indication of the heath of each tree, such as flexure. Group parameters give an indication of the forest stand as a whole.

When all initial parameters are calculated, the forestry model will calculate secondary parameters. Python scripts supported by the ArcGIS environment will be used to assist the entire procedure from data analyzation to model outcome. Finally, with the RIEGL data as well as the manual forest assessment will evaluate the Microsoft Kinect data and the forestry model.

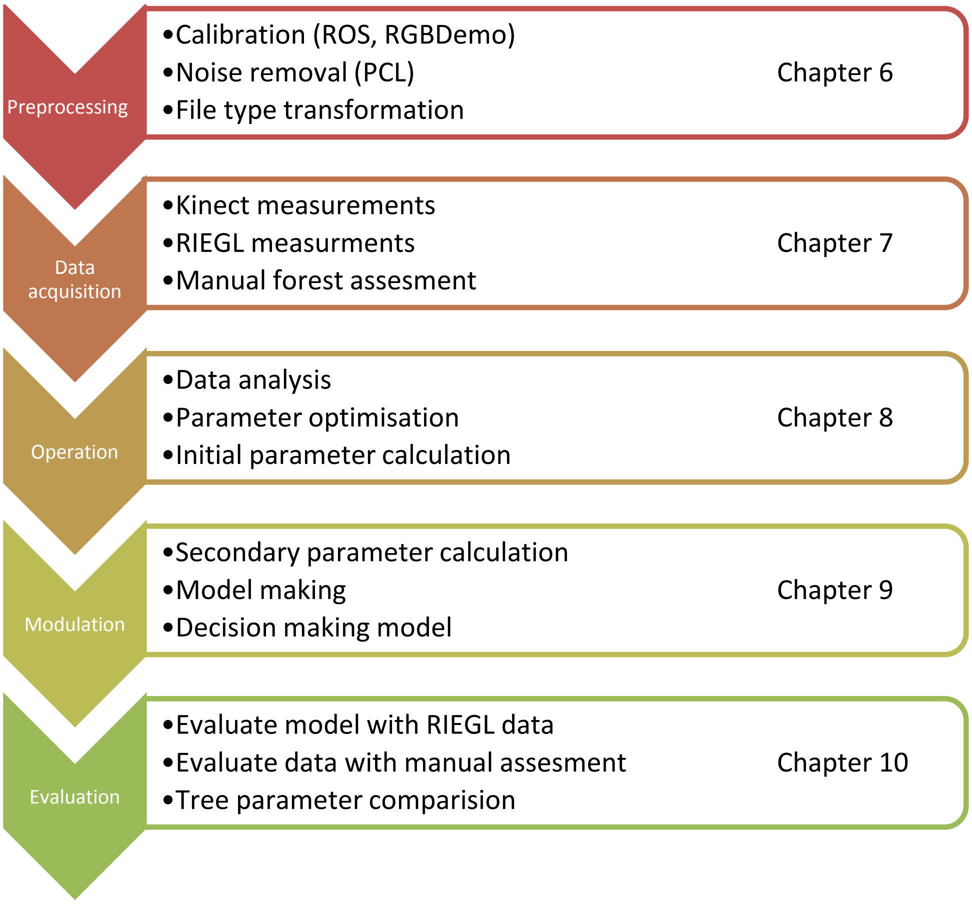


Figure 6. Flowchart of methodology

4.1 Software overview

This research made use of various software budles, this could create confusion . Therefore this overview was created to create some clearance on when which software package was used.

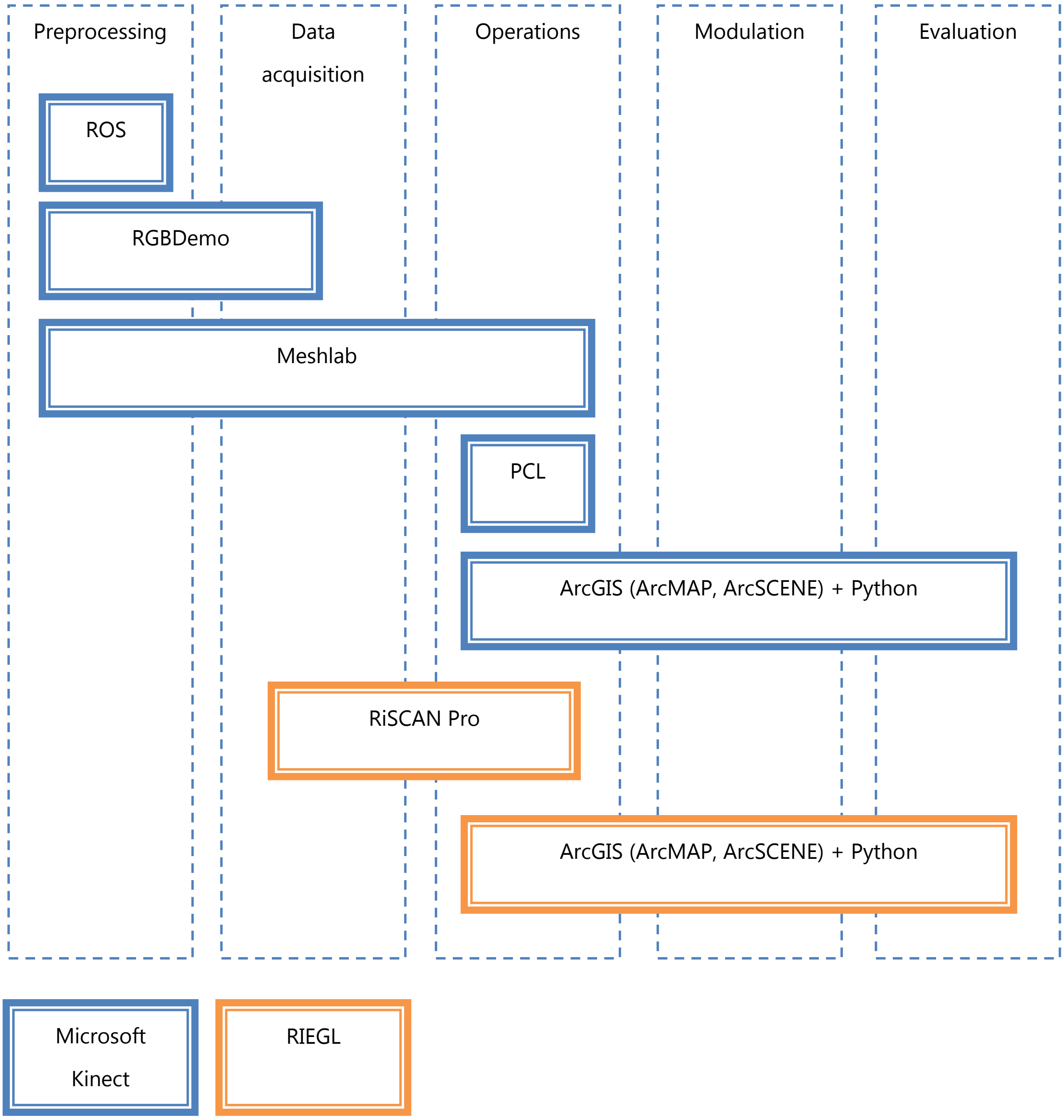


Figure 7. Flowchart of used software

Chapter 5. Experiment setup

This research is focused on three procedures; de Microsoft Kinect analysis (1), the RIEGL scanner validation (2) and the manual forest assessment (3), each of which requires a specific setup.

5.1 Microsoft Kinect

As stated the Microsoft Kinect started out as a video gaming device. Since then, the abilities of the Kinect have been tested for purposes other than gaming. In table 1, an overview of the Microsoft Kinect properties can be seen, compared to the more advantaged RIEGL scanner.

	Kinect	RIEGL VZ-400
Minimum range	0.7 meters	0,5 meters
Maximum range	15 m	700 m
Optimal Range	1.2 to 3.5 meters	-
FOV	57 X 43	100 X 360
Frame rate	30 Hz	300.000 Hz
Accuracy	0.2 (0,5 m distance) 40 mm (5 m distance)	5 mm
Resolution RGB	640-480 pixels	-
Price	80 euro	10.000 euro

Table 1. Kinect (Khoshelham and Elberink, 2012) and RIEGL (RIEGL, 2013) properties

Because the Microsoft Kinect needs to be able to operate in the field, power supplies are needed in order to operate. This research used two methods. One was a small generator with LBG (Liquefied Bio Gas) driven supply and another were a 12V battery was connected with help of 12v to 220V transformer. The last method proved to be the most useful for working in field conditions. The Microsoft Kinect 360, the successor of the Microsoft Kinect, has the ability to power itself directly through a laptop battery.

In the field, the Microsoft Kinect was connected to the battery and transformer on one end, while connected to a laptop (on battery) at the other end. This setup proved to be compact enough to measure small and compact forest patches even within tree structure. In each plot a central tree was chosen, usually a larger tree the in middle of the plot, and a stick was planted that was corresponding to 1,30 meter above ground.

5.2 Microsoft Kinect sampling scheme

Because the Microsoft Kinect has the ability to scan continuously, no static measuring positions were needed. The steps were the images from different points of view needed to be merged are therefore no longer necessary. One continuous scan of each plot is made in order to further analyze the results.

A limitation of the Microsoft Kinect scanning is that it needs a central point to build the remaining points to. When the central point is lost, or when the points already having a steady position to central point are lost, the device stops recording and give blank data. The best method of point acquirement therefore found, is to move slowly alongside a central point, in this case a large tree in the center of the plot, to be able to record the surrounding trees.

5.3 RIEGL setup

The RIEGL VZ 400 scanner is a terrestrial laser scanner mounted with a Nikon D700, which comes with the RiSCAN Pro software. It has been used in a variety of different scientific fields, including forestry (Calders *et* al. 2011). The RIEGL device was setup with 4 to 2 positions per plot. While standing on a tripod around 1.5 meters high, a RIEGL VZ-400 was placed with a digital camera on top. On each plot, around 20 to 40 reflectors where placed in order to co-registrate the scan points on each plot.

5.4 RIEGL sampling scheme

The RIEGL sampling scheme differs from the sampling scheme of the Microsoft Kinect because of the broader range of the RIEGL scanner. In two of the plots (deciduous and coniferous), four scans on four scan positions were performed. The shrub plot was measured using three scan positions. The mixed plot appeared to be sufficient with two scans.

5.5 Manual forestry assessment

The manual forestry assessment is performed by 10 forestry students of the Department of Forestry and Nature management at Wageningen University. In each of the four plots, they were asked to fill in a number of forms describing which trees in the coming 5, 10, 20 and 50 years would be marked for thinning and which ones would be marked as dominant trees. The documents can be found in Annex 1a,b,c and d. Each student forester is asked which trees to eliminate between each time interval. Eliminating the trees with a cross and marking dominant trees with a D (of dominant tree). Trees without markings were considered normal trees, which could be placed in one of the two in further time intervals.

Besides the decision making process, each tree selected in the plot for research was measured with a tape measure to analyze the real DBH, in order to compare this data, to that of the Microsoft Kinect. The height was also measured and used as a constant function in the forestry model.

Chapter 6. Preprocessing

Preprocessing of the Microsoft Kinect consisted out of the creating stable setup on two OS and performing a number of calibrations which will function as a basis for the rest of the research. The Microsoft Kinect was configured as explained in Annex F. The setup was performed on two different OS, Windows 7 and Ubuntu 11.X. In sections 6.1 and 6.2, the calibrations inside and outside will be explained, followed by the results. Hereafter a small conclusion will summarize the preprocessing.

6.1 Calibration

In this research, a number of calibrations were performed in order to standardize the results from the Microsoft Kinect. A checkerboard analysis was performed in the Robotic Operating System (ROS) development kit to research the depth and RGB data. The Robotic Operating System provides a number of libraries (C++ and Python) to help software developers to create robotic applications. ROS is licensed under an open source, as a BSD license. Diamondback is the most recent ROS distribution and contains support for the Microsoft Kinect as well as Point Cloud Library (PCL). These calibrations were performed on the Ubuntu 11.0 Operating system.

The accuracy and precision of the Microsoft Kinect has been proven to be very high (ROS 2, 2013), however the Microsoft Kinect still needs to be calibrated. The color and depth calibration were done using checkerboard stereo calibration. This estimates transformation between 2 cameras and thus creating a stereo pair. The relative position between two sensors is fixed (depth and color), and if the computed markers of an object relative to the first and second sensor, those markers will relate to each other and will be able to the compute the position and orientation of the 1st sensor to the 2nd sensor. A more technical description about the underlying calibration methods is provided by (ROS 3, 2013).

A checkerboard analysis was performed in the ROS development kit to research the depth and RGB sensors. Because the RGB and IR cameras display different color outputs, the proposed calibration technique uses a regular checkerboard target of size 50 by 70 cm, which is visible in both sensors spectra. The checkerboard is printed on normal paper, to minimize reflectance.

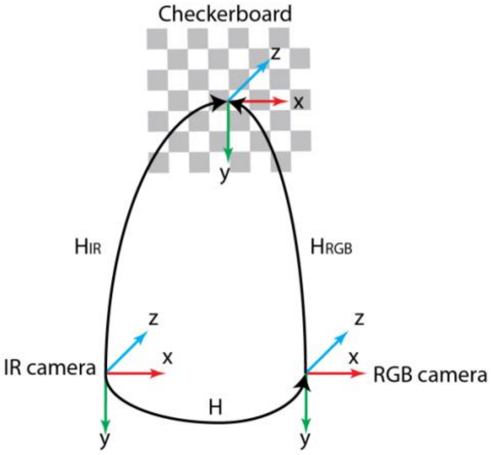


Fig 8. Checkerboard calibration and distance calculation (Mertz et al, 2012)

Hereafter the Microsoft Kinect could be calibrated by moving the checkerboard in front of the camera and wait until the checkerboard is calibrated. This process was performed with ROS calibration commands. The process of calibration is done by selecting number of "tie points" in the image manually and storing this in the calibration software. A successful checkerboard analysis in Diamond back will result in an image in which the real world straight edges will appear straight in the corrected image.

This analysis uses the known distance on a checker board to analyze the precise distance anywhere else on the same distance. This method creates a calibration for the color and contrast sensors of the Microsoft Kinect. In order gain good values for further research, a regression function was needed for other software to obtain valid results.

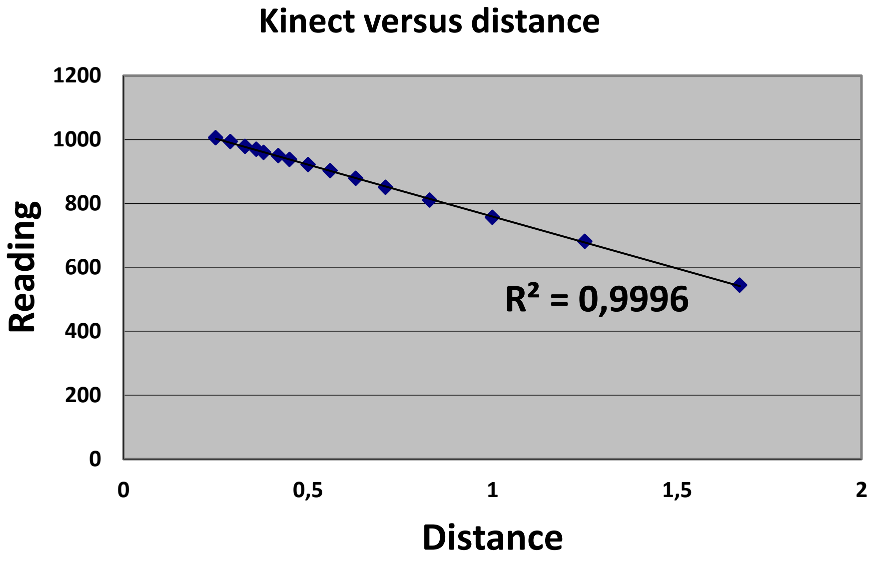


Fig 9. Kinect versus distance

After calibration, both cameras achieve reprojection error between 0.15 and 0.17 pixels, which is better than the original projection given by the Kinect sensor. The reprojection error without calibration of the IR camera is estimated as larger than 0.3 pixel and that of the RGB camera is larger than 0.5 pixel (Konolige and mihelich, 2011).

6.2 Outside calibration

After the inside calibration was performed and the depth and color was calibrated accurately, an outside calibration was performed using the Microsoft Kinect and a manual measuring tape on a distance of different distances with the same targets as during the inside calibration. A number of trees were measured with both devices. Resulting in the following diameter data;

Tree number	Microsoft Kinect (-)	Measurement (cm)
Tree 1	0,5566	63
Tree 2	0,4803	51

Tree 3	0,3207	43
Tree 4	0,1827	21
Tree 5	0,1424	18

Table 2. Outside Kinect calibration at 1 meter distance.

This data was further used to calibrate the linear units, which were not specified as projected on an own projection. The data here presented is heavily supported by the two initial calibrations, with ROS and RGBDemo, on its own measurement system and on a variable distance and therefore do not have much functions outside of this research.

Chapter 7. Data acquisition and description

After the calibration, the data was extracted from the field. The data acquisition was made with a few fieldwork criteria:

- The data should be collected roughly in the same weather conditions
- The data should be collected without or limited obstruction of any anthropogenic objects
    - (not counting production structure of forest plantations)
- The data should be collected in roughly the same season

Hereafter the plots were selected on the Oostereng.

7.1 Kinect data extraction

The actual data acquisition of the Microsoft Kinect was done on each of the four plots, on the same day. This resulted in the following number of data points (vertices) acquired per plot. The scanning time varied from 5 to 15 minutes per plot and each plot was measured in one session.

Type	Number of vertices
Deciduous	2,473,483,233
Coniferous	3,194,372,372
Mixed	1,232,123,679
Shrub	1,546,854,345

Table 3. Number of vertices per forest stand measured

7.2 RIEGL data extraction

The RIEGL data was extracted on the exact same four forest stands as the Microsoft Kinect. A point cloud was extracted with a number of points.

Type	Number of point
Deciduous	22,678,328,849
Coniferous	23,984,940,844
Mixed	12,932,145,002
Shrub	16,112,582,205

Table 4. Number of points per forest stands measured.

7.3 Manual forest assessment

The manual forest assessment was preformed, of which the results can be viewed in Annex D and E. Most of the data was written down and hereafter digitalized. The data was later analyzed in Microsoft Excel.

Chapter 8. Operations

8.1 Noise Removal

Noise removal was performed manually for large noise clouds in Meshlab and systematically in PCL (Point Cloud Library). PCL is an open project focusing on the analysis of 2D and 3D image and point cloud data alike. PCL is released under a BSD license. It offers numerous methods for analysis and modifying data such as applying different filters, surface reconstruction and segmentation. The PCL is able to work cross platform on Windows OS and Ubuntu. This research was performed on Windows OS with the PCL 1.7.0 version.

Firstly the data was transformed to a XYZ data type format. Noise removal was performed in PCL using the MovingLeastSquares method. This method smoothens and improves the normal point cloud (PCL 1, 2013). An example can be seen in figure 8.1. An example script used in this research can be found in annex H. It was hereafter exported to a ply file type.

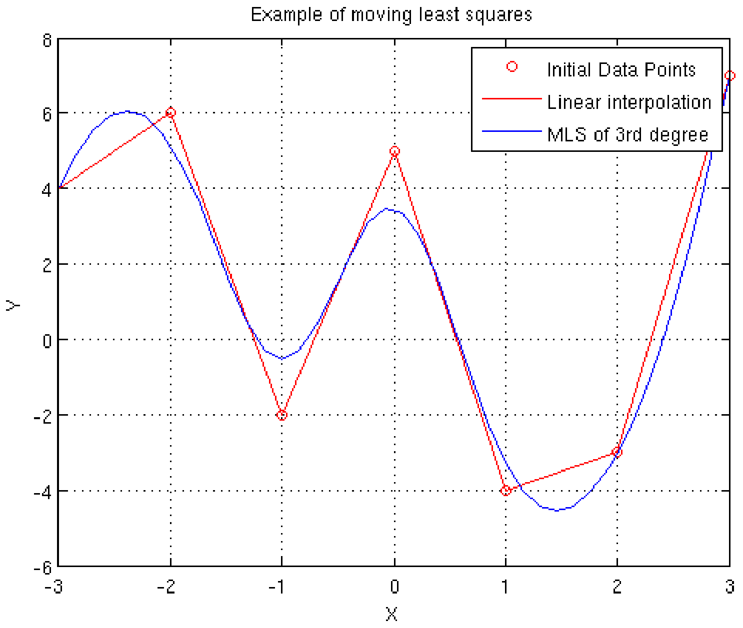


Fig 10. Example of moving last squares

8.2 Selection

The analysis of the data, besides the selection which was performed in Meshlab v.3.2.1, was performed in ArcGIS 10.0. As described in the literature review, foresters have standardized diameter at DBH or 1,30 meters from ground level. Therefore, in this research the Microsoft Kinect grabbed a slice of data between 1,25 and 1,35 meters. The slice selection was calibrated by using manual indicator points in de field. The selections in this part were performed inside the Meshlab v1.3.2 software package. Meshlab v1.3.2 is an advanced 3D meshing software. The open source software was developed in 2005 and offers users various functions visualizing specific point clouds and meshes.

Fig 11. Selected DBH (in red)

After all vertexes between the preferred distances were selected, a selection filter was applied, deleting large noise clouds of excessive vertices and exporting the data as a XYZ file. After XYZ to SHP file transformation, which can be found in annex J, noise clouds that couldn't be removed by the Point Cloud Library, were also removed manually in Meshlab.

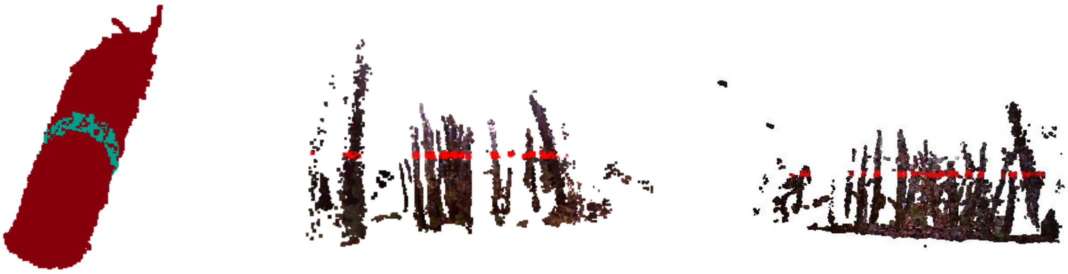


Figure 12. Selection procedure

The figures show a horizontal view of a selection in Meshlab v1.3.2 of a deciduous forest and a mixed forest stand and a close up of a tree trunk selected between 1,25 and 1,35 meters of ground level. Notice also a large noise cloud on the right of figure 15.

The RIEGL data was selected in RisCAN pro. An area between 1,25 and 1,35 meter high was selected. This resulted in 4 slices of data points from the 4 forest stands. The procedure for each forest stand was first to align the data from each position to each other with the image made in each forest stand. Hereafter the data was from all excessive data obtained during the scan. This was done by removing outliers and removing data outside the plot manually (3). The data can now be used to select the preferred height. The process of selecting the preferred height was done automatically, based upon the RIEGL data. The files were exported as LAS file types to ArcGIS.

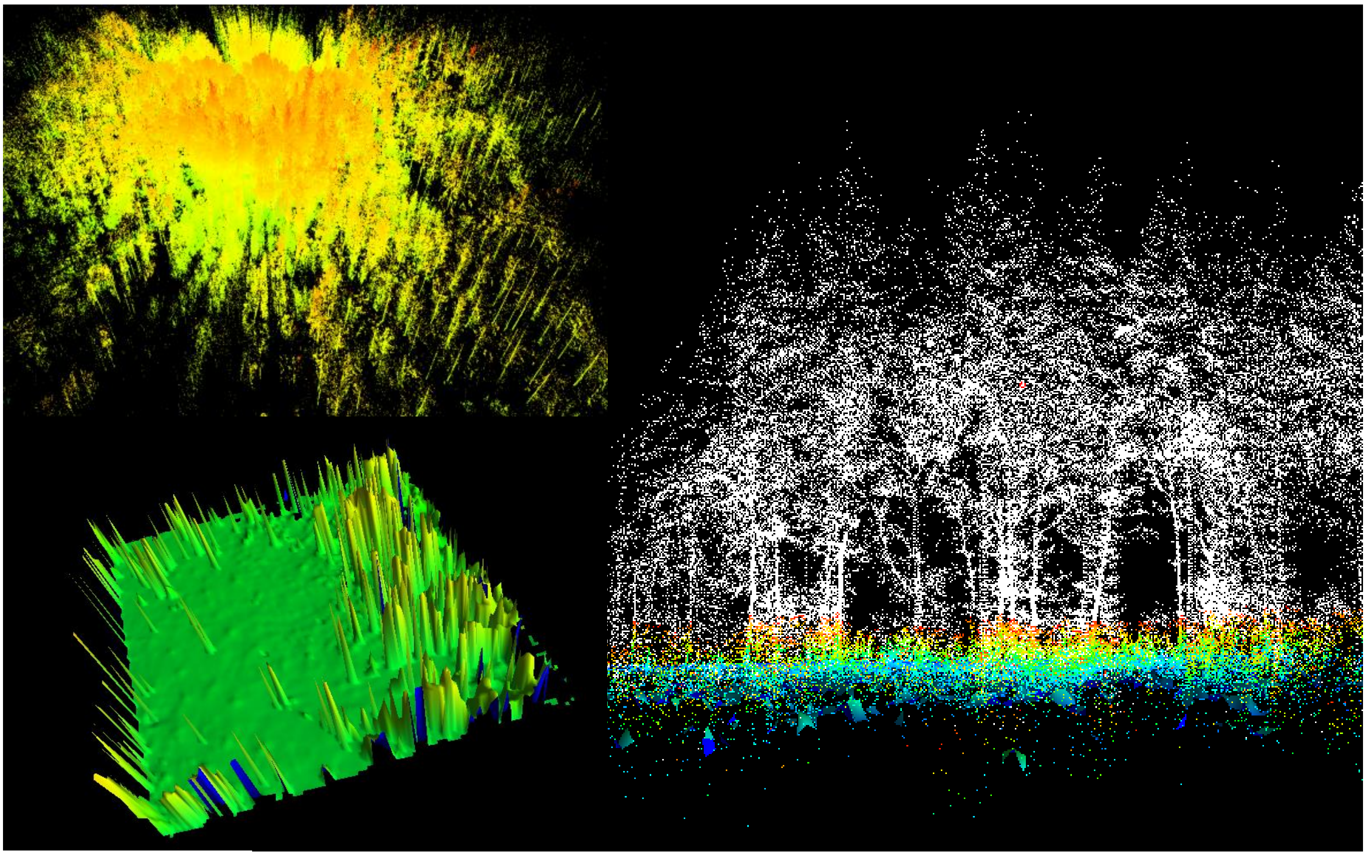


Figure 13. RIEGL selection

Aligning scan positions in RiSCAN Pro, Removing outliers and cutting the patch manually out of the data while selection the preferred height data.

8.3 Grouping points to featured trees

Both the RIEGL and Kinect data was used in the same procedure to group points. In which, each of the four point clouds were clustered following the same procedure and was formatted into a python script to function automatically in ArcGIS. First all point features were buffered with a diameter of 1 cm, the buffers were hereafter dissolved, transformed to line features and back again to polygon in order to distinguish different trees features. This resulted in a table were the quantity of trees was presented.

The next step would be to select each point inside each buffer, and group those within each polygon. Hereafter a convex hull was created around each selected group of points. Each convex hull symbolizes a tree. Also each convex hull polygon was an entry in the table.

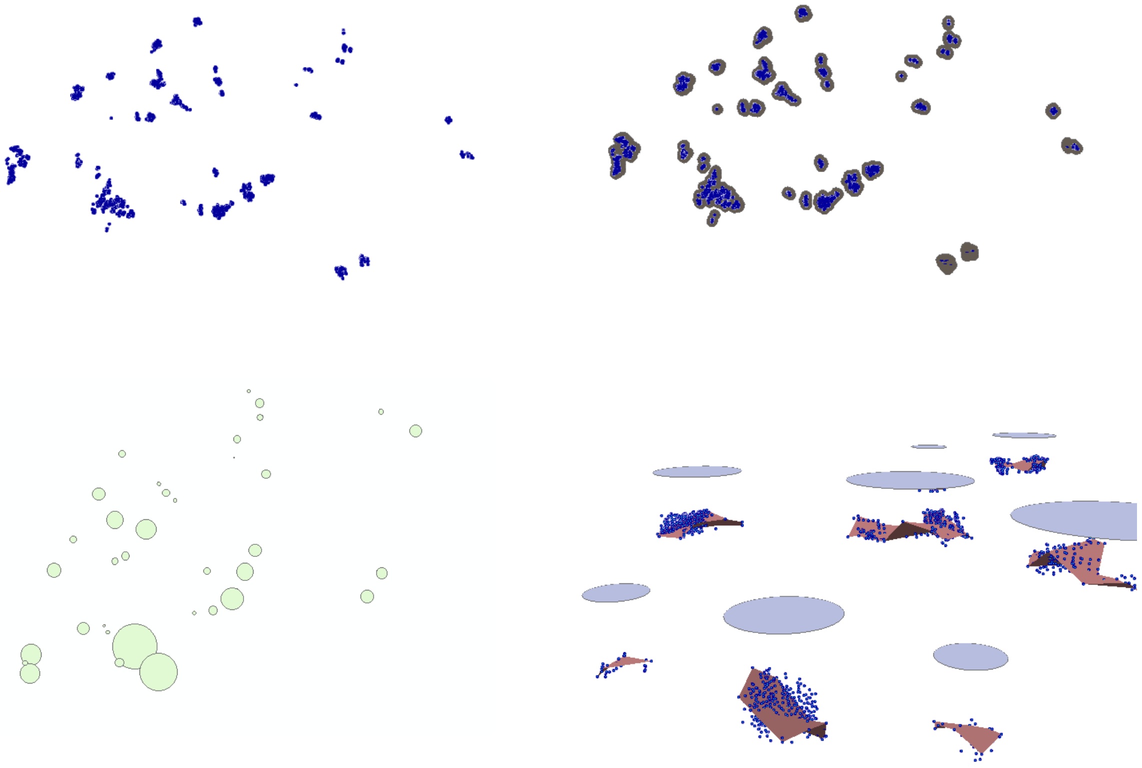


Figure 14. Creation of tree features

The images visualize a point cloud, extracted and visualized in ArcSCENE. The point cloud is then buffered and surrounded with a minimal bounding geometry polygon which encompasses all of the points. The points then can be grouped, effectively creating the tree features.

Measured tree features, especially the smaller ones, tend to have an irregular shape due to crude point density of the scanners. Therefore a convex hull doesn't cover the entire tree structure properly. A more round geometry type would come closer to a realistic tree shape. A method available in ArcGIS, is the circle method in minimum bounding geometry, using a circle to be drawn around the point clouds, resulting in a more accurate tree shape. This shape optimization inside the data analyzation model was used to optimize the convex hull, to create realistic tree features.

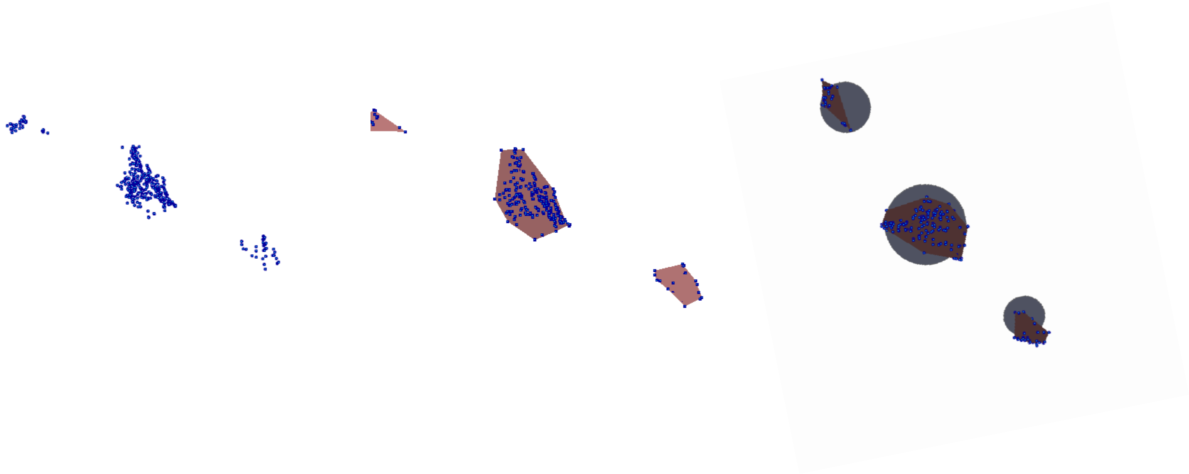


Fig 15. A horrible distorted tree feature (in blue) being shaped back to healthy tree (in red) by using circle shape optimization.

8.3.1 Noise reduction

Noise elimination is a difficult problem when dealing with automatic data extraction. Although noise was removed by use of software (PCL, Meshlab and ArcGIS), it still accounted as a large problem when noise clouds are loaded in decision making models. Wrong decisions could be made. However, an algorithm was developed which localized irregular shape patterns. The noise (of trees that were not really trees) was removed automatically. The algorithm was developed by creating two polygons by minimum geometry function, a convex hull and a rectangle of each tree. Then the polygons were compared and when found to dissimilar, removed from the outcome. This means that trees with large noise clouds on each side where deleted because the shape was found to irregular to be a tree.

8.4 Calculation of tree parameters.

For each of the initial tree metric data, a number of parameters were calculated. The parameters were extracted from the finished results. These parameters were needed as initial parameters for calculation of the secondary parameters and the outcome of the decision making model. Remember these calculations were still performed in the units defined by the Microsoft Kinect.

8.4.1 Position

The position of each tree, which was defined as the area of the total point cloud, was automatically extracted in the Microsoft Kinect data and was selected as the entirety of the convex hull surrounding each point cluster. The position of each tree will form the basis of each future tree placement in the forest.

8.4.2 Area

The area, which can be defined as the area covering the forest stand, is calculated by the combination of Kinect parameter values of distance. For each tree, the distance to its neighboring tree clusters is calculated, with the proximity analysis, resulting in this forestry parameter.

8.4.3 Tree quantity

The tree quantity is defined as the amount of trees selected on each plot. This parameter is estimated by the number of features selected in the model.

8.4.4 DBH

The diameter was calculated using the area of the convex hull in 2D, by exporting the data to ArcMAP and calculating the area on a 2D environment. This resulted in a field with a DBH value for each featured tree.

8.4.5 Flexure

The shape of the tree was calculated using the DBH data in the slope function. After conversion to a raster dataset, a slope analysis was performed. The slope values where then extracted to the features values by using zonal statistics and a sampling tool. This resulted in a new field with the calculated slope values, in the final table for each feature.

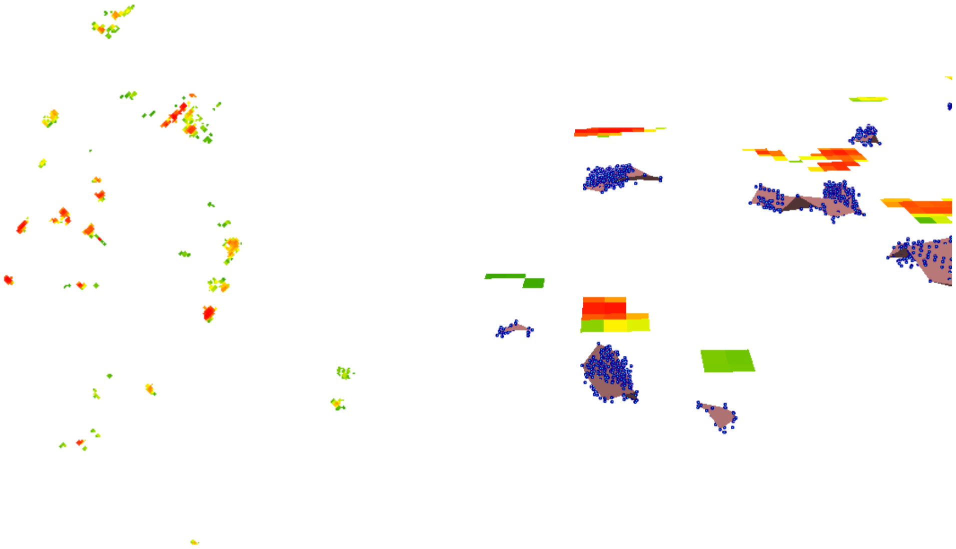


Figure 16. Slope in a mixed forest stand in which the colors red, yellow and green symbolize the steepness of the slope, from red as steep to green as flat.

Red can be seen as very steep and green as almost leveled. As can be seen there is some difference between the slopes of different trees. The slope is calculated using the slope algorithm looking at the distance between the points and their neighbors effectively measuring the steepness of the distance between these points. This resulted in slope values for each of the tree features.

8.5 Conclusion

This chapter we have shown the ability to select and group data point clouds with different methods for both the RIEGL and Kinect data. The buffering point's method was chosen to encompass all of the data points for the trees and dissolve certain type of noise clouds. The model optimization procedure showed two methods which decreased the change of a noise cloud to be classified as a tree, as well as optimizing the realistic biomass values of trees. The parameter calculation section explained the construction of the initial parameters. These will be used in the next chapter to use a input for the forestry decision making model. Finally, a brief description about some of the manual file type transformations was explained.

Chapter 9. Modeling

The forestry model build is a simplification of other forestry models described in the literature. Were only a few parameters are actually obtained from the Microsoft Kinect and RIEGL data, the majority of parameters are considered constant or none existent.

9.1 Parameters

The model was developed with in python as an ArcGIS plugin. The model was designed as a simple growth model, and decision making algorithm. Therefore the model requires only few initial stand parameters, extracted from the Microsoft Kinect. These initial parameters can be dynamically inputted out of the models by the GIS environment (ArcGIS). The initial parameters, as explained in the previous chapter of this research include,

- **Area**
- **Position**
- **Tree quantity**
- **DBH**
- **Flexure**

Secondary parameters which are derived from the initial parameters are the following.

- **Type of the forest**. The type of the forest was determined by looking at two parameters, the density of the forest and distribution of trees. It was found that forests with a higher density were usually none production forest.
- **Health,** the health was calculated by the flexure, place and density of the forest structure
- **Volume,** the volume was calculated using the DBH and measured stem height.

Besides these parameters a few others were derived from other measurements (by user input) and through literature research. These parameters are considered constant, emphasizing the simplicity of this model.

- **Height**, depending on the species a steady value was measured during the manual forestry assessment.
- **Specie**, beyond the scope of this research, was provided by the user.
- **Growth factors** were provided from literature research.

Other parameters are considered constant and are not included in this model.

9.2 Model creation

9.2.1 Python description

Among all the available script languages, Python was found to present a unique compromise between the following features: it is (a) open-source; (b) available on the main operating systems; (c) object-oriented; (d) simple to use with syntax sufficiently intuitive for non-computer scientists (e.g. for biologists); (e) interactive: it allows direct testing of pieces of code without requiring a compilation process; and (f) has excellent support for integrating code written in compiled languages (e.g. C, C++, Fortran). Additionally, the Python community is large and very active and a large number of scientific libraries are available and can be imported into a program at any stage of model development.

9.2.2 Build up

The model was constructed using a python plugin in ArcGIS. Each of the parameters was tested to determine forest stand and tree characteristics. Hereafter the model looked at the amount of trees, dividing them in 5 categories from low to high potential trees, based upon the tree parameters. Next the model selected a minimum number of trees to be thinned. After almost all tree features were selected as thinned or dominant, the model gives a table output which stated at what time interval a tree is selected a thinned and the reason of the thinning. In total 4 time intervals are existent and therefor 4 outcomes are expected.

This model uses growth factors of different species conceived out of yield tables. The mixed specie stand was based upon a number of growth factors. The growth factors, used by the Forestry Commission of the UK were used as basic outline, while the growth factor of the Douglas fir (an exotic species), the ISA tables were used.
The decision making model was constructed using forestry principles such as described in Bos- en Natuurbeheer by Den ouden *et al*, (2012).

The decision making model thinned upon three reasons:

- A distance too short to a dominant tree
- A size too small to further develop into a dominant tree
- A fixture too steep to further develop into a dominant tree

The values for the distance and size were calculated taking the estimated circumference for the time interval and calculating the bottom 20% of the trees with the lowest size and smallest distance. These trees would then be marked thinned. The slope was a constant value therefor only applied in the first thinned interval.

9.3 Model output

The model output was generated in the ArcGIS using the Arcmap symbology. The symbology was rendered using a legend which was made using the outcome of the model. The trees were rendered using the original circumference of the trees measured. In each of the four outcomes after 10, 20, 40 and 60 year a layer was rendered, in which the circumference would be a static parameter. In each outcome, the outcome will be updated with the information calculated by the decision making model. Each of the tree features gets assigned a type; cut, dominant or undecided and when the type cut was assigned another type was assigned in which the decision making model assigned the reason of cutting the tree; over size parameters, proximity parameters and slope parameters. The primary reason for the cutting will be displayed in a label in the outcomes. In this model; red was given for to cut or already cut trees, black as undecided for this time interval and green as potential trees.

Below is shown a model output as depicted in ArcGIS. As can be seen the model selected four trees as dominant trees with potential wood production. A number of smaller trees were selected for thinning to create place for the other trees. The red dots are trees already thinned trees, in the first thinning round. The black trees could be selected for thinning in the next round or can be placed in the dominant tree category.

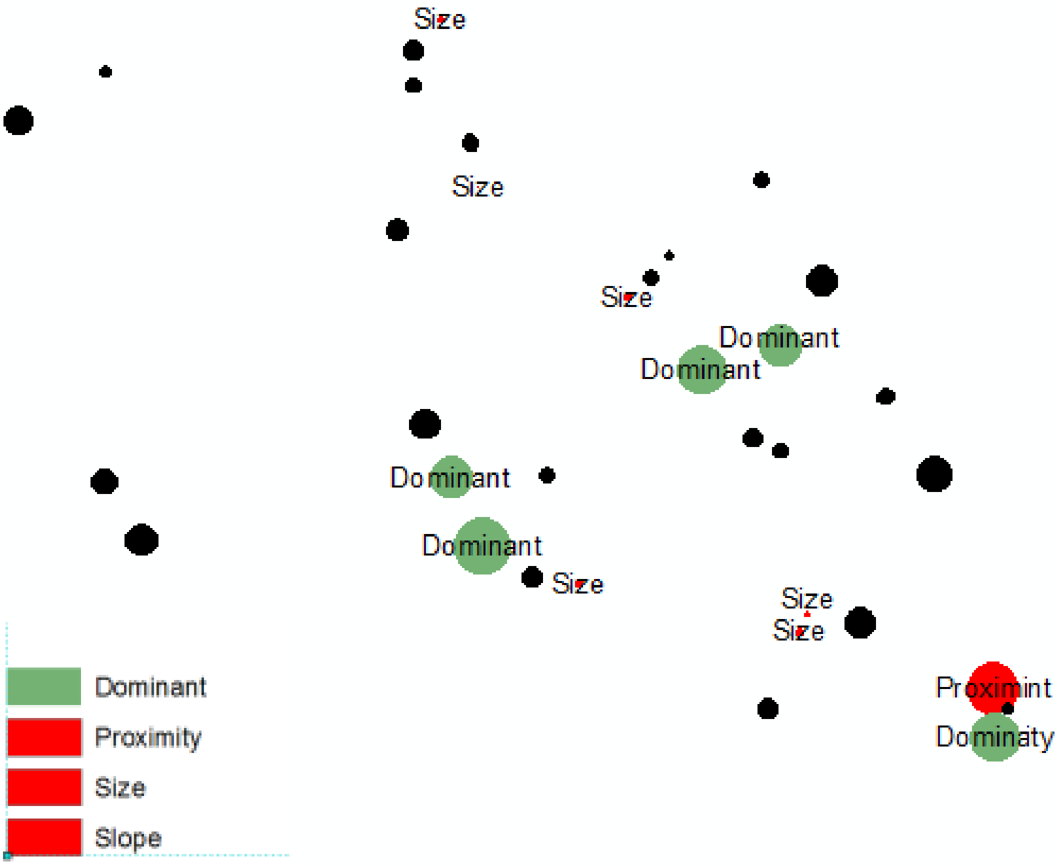


Figure 17. Example of a model output after 10 years of deciduous stand with label giving indication about thinning criteria.

Chapter 10. Validation and evaluation

In this chapter the gather data will be gathered, validated and evaluated. First the Microsoft Kinect data will be tested on the quantifications parameters of completeness, correctness and overall quality of the quantitative data; the RIEGL data will be tested on the same parameters and compared to the Microsoft Kinect data, hereafter both datasets will be compared with the validation dataset from the manuals forest assessment. This will validate the outcome of the forest stand measurement by both devices

Next the quality of the diameter data will be tested by comparing the RIEGL and Microsoft Kinect diameter data to the diameter values of the manual forestry assessment data. This will validate the measured data of individual trees, in order to measure the accuracy of the measurement design.

Finally, the dynamic forestry decision making model output will be compared for the Kinect, RIEGL and manual forest assessment data. The difference between the three datasets will be highlighted and explained. This analysis will be performed in order to find the accuracy of the model and the decision making process.

10.1 Quality of data

The data of all the trees measured in each stand was assembled and checked for their quality. The amount of trees measured and the amount of trees correctly classified as tree are an important measuring tool for determining the data's quality. Because the tree measurement was different for each forest stand, the difference between each of the stands was highlighted. Also a comparison between the quality of the RIEGL and Kinect was given.

10.1.1 Completeness, correctness and quality of Microsoft Kinect data

The completeness, correctness and quality of the trees present was measured according to the measuring algorithm designed by Heipke et al, (1997) and further developed by Xiao, (2012). In this evaluation algorithm, the completeness is described in equation 10.1. In which TP can be defined as True Positive, the amount of trees measured by the model, and FN as False Negative, the amount of real trees that have been removed. The correctness was measured and described with equation 10.2. In which TP has the same definition as before and FP is described as False Positive or the amount of noise data falsely classified as tree. The quality was calculated with equation 10.3. The data can be seen as a summary from the correctness and completeness.

$$Completeness = \frac{TP}{TP + FN}$$

Equation 10.1, Completeness

$$Correctness = \frac{TP}{TP + FP}$$

Equation 10.2, Correctness

$$Quality = \frac{TP}{TP + FP + FN}$$

Equation 10.3, Quality

The data was compared with the manual forestry assessment, which means that a 100% match means the data is identical to the trees selected in the forestry assessment. Basically for each forest stand, a number of trees was chosen in the manual forestry assessment which could to be measured, the amount of trees collected by the devices resulted in a completeness value. A 100% values means all trees selected in the manual forestry assessment were measured by the device.

Sometimes however also "phantom" trees were detected by a measurement device. These trees would mostly originate from false data or noise clouds in the data. The correctness value gives an indication of the amount of phantom trees measured in the forest stand. A value of 100% represents no noise clouds or phantom trees detected.

	Deciduous	Coniferous	Mixed	Shrub
Completeness	100%	100%	60%	75%
Correctness	95%	98%	82%	76%
Quality	**95%**	**98%**	**42%**	**51%**

Table 5. Completeness correctness and quality of the Microsoft Kinect data

The data, available in Annex D, for deciduous and coniferous forest stands is proven to be of a good quality. The mixed and shrub outcome on the other hand is proven to be of lower quality.

The deciduous and coniferous tree stands, as can be seen in chapter 3, were planted in a typical production stand position, resulting in almost no noise between stems and creating an almost perfect completeness percentage. The quality therefore is mainly determined by the correctness factor, which indicated there are still some minor noise clouds interfering with the model by creating false trees.

It also can be seen that the coniferous forest stand has a higher correctness level than the deciduous forest type. This is caused by the difference in age and the stand characteristics between coniferous and deciduous forest types. The Douglas fir was measured in an old age growth stage, while the mainly birch trees were from a much younger stand. The observed oak and birch trees has still some lower hanging branches at the DBH level, where the slice used for the model was extracted. Therefore the correctness is the most determining factor for the quality of the Microsoft Kinect data in commercial forest stand with monotonous tree production.

The mixed and shrub forest stands, do have a larger number noise clouds between the stems than the deciduous and coniferous forest stands. These noise clouds were a result of low hanging leafs and branches, blocking the stem resulting in a lower completeness level. Therefore two types of errors are in effect, resulting in a reduction of the quality of the data. Noise clouds resulting in a smaller correctness value similar as observed in the deciduous and coniferous forest stands and also the effect of the density from the noise cloud reducing the ability to measure the stem, which indirectly leads to the model failing to determine a stems position and other tree metric data. In figure 10.1 a crude unedited image of the mixed forest stand is shown as acquired by the Microsoft Kinect. It shows noise clouds between the trees. These noise clouds are low hanging branches.

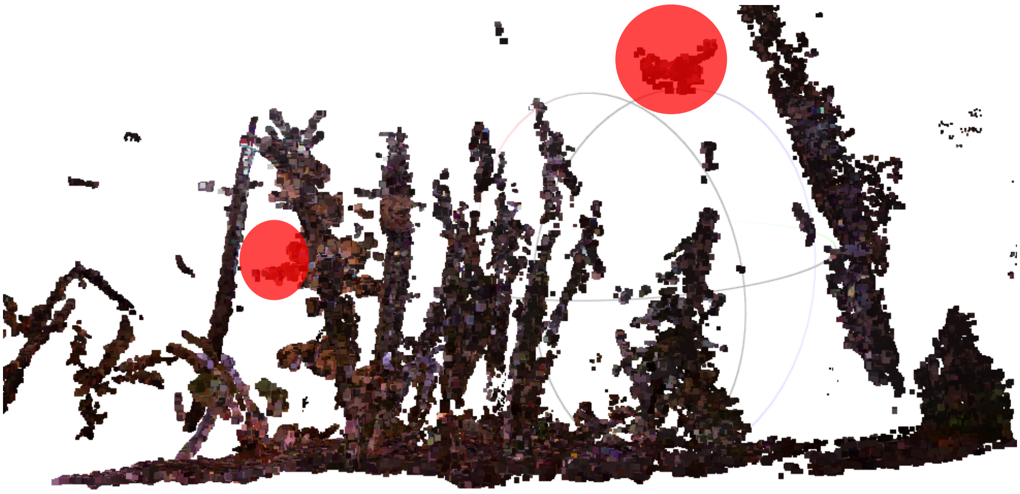


Fig 18. Noise clouds in a Microsoft Kinect image.

Another cause for lower completeness and quality within the shrub and mixed forest stand is the disability by the researcher to measure within the structure because of the density. This is causing some of the trees lacking in the completeness of the dataset. One of the main assets of the Microsoft Kinect is the mobility of the device, by letting the researcher focus more on points of interest within the data acquisition; however this mobility is limited by density.

10.1.2 Completeness, correctness and quality of the RIEGL dataset

The RIEGL data was processed with the same method the Kinect data was processed. Both the model for parameter extraction and the discussion making model were able to gain results. The completeness, correctness and quality of the RIEGL data were calculated following the same procedure as the Microsoft Kinect was calculated.

	Deciduous	Coniferous	Mixed	Shrub
Completeness	100%	100%	75%	92%

Correctness	100%	100%	92%	87%
Quality	**100%**	**100%**	**67%**	**79%**

Table 6. Completeness, correctness and quality of RIEGL data

The data acquired for both of the production stands proved to be complete and therefore the quality was perfect. All of the trees were accounted for and no noise clouds were wrongfully classified as trees. The mixed and shrub forest stands were a different story. The completeness in especially the mixed forest stand resulted in a low percentage which was caused by the lacked a large number of trees. This was mainly caused by the acquisition method, with only used two measurement positions and lack of mobility of the RIEGL device to focus on parts of interest. Because noise clouds or even whole tree features blocked some of the other tree features, lack of data resulted in a smaller completeness percentage.

10.1.3 Comparing quantitative data

Compared to the Kinect data the RIEGL data has overall a higher quality. The completeness from both the productions forest stands has a high percentage and therefor a good quality, only the RIEGL data showed no errors within measurements. Both the shrub and mixed stands have a smaller percentage in quality for both devices. However the correctness, which is caused by noise cloud and other data errors, is much smaller within the RIEGL device, than the Microsoft Kinect. The only advantage the Microsoft Kinect has over the RIEGL device is the increased mobility and the ability to focus on specific areas of interest, which can increase the correctness and quality of acquired data.

10.2 Diameter quality assessment

Besides the quality of the tree count, also the diameter of the individual tree diameter can determine the quality of the measurement technique. Both the data of the Microsoft Kinect and the RIEGL were tested using statistical methods such as the RMSE and R squared.

10.2.1 Diameter quality assessment Microsoft Kinect data

The diameter quality is determined by comparing the Microsoft Kinect data, as can been seen in Annex D, to the manual forestry assessment data. The results of the diameter at DBH of the Microsoft Kinect were compared to the diameter values in centimeters from the manual forest assessment. The average and standard deviation were calculated as well as R squared and the RSME.

The RMSE was calculated using the following formula:

$$RMSE = \sqrt{\frac{\sum \ (MFS - K)^2}{n}}$$

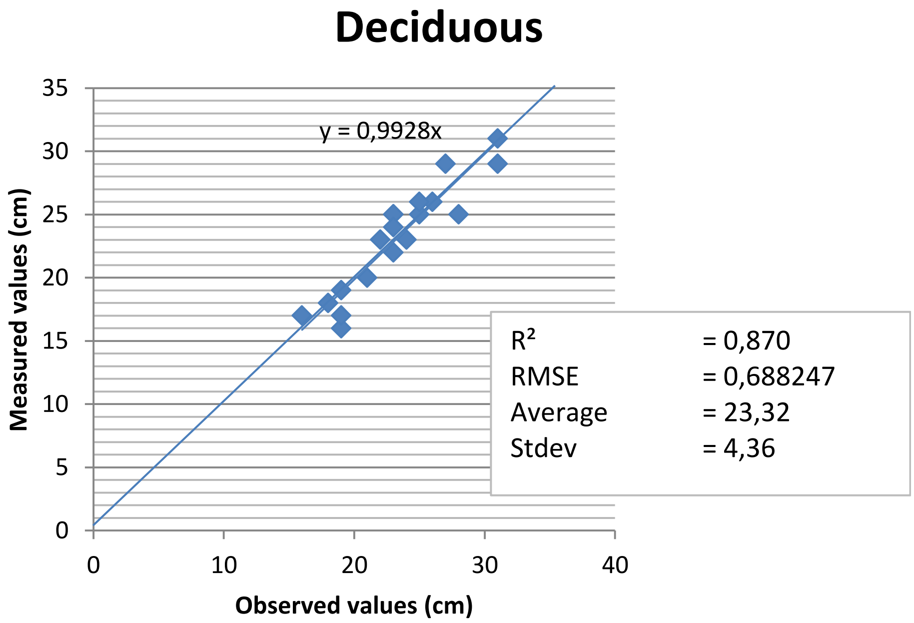
Equation 10.4, The RMSE in which MFS is the manual forestry assessment data and K the Kinect data, n the amount of trees.

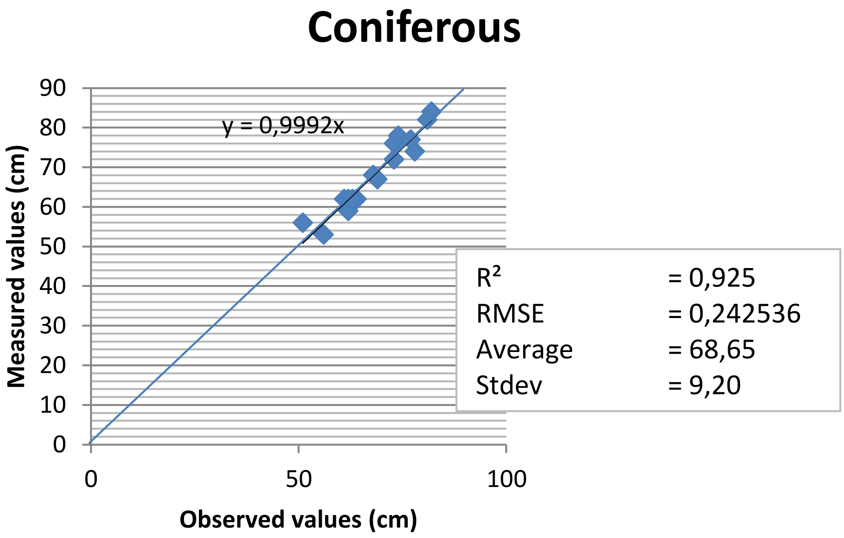
The R squared was measured using the following formula;

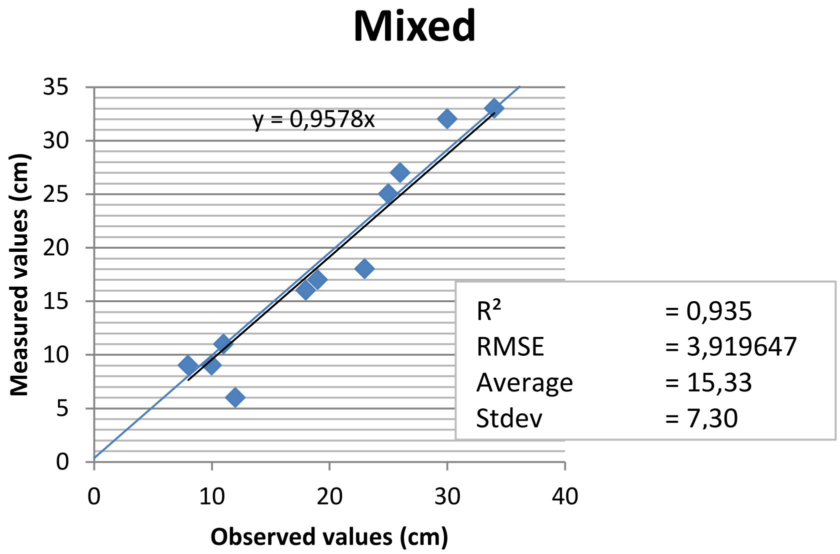
$$R^2 = \frac{\sum(X - \overline{X})(Y - \overline{Y})}{\sqrt{\sum(X - \overline{X})^2 \sum(Y - \overline{Y})^2}}$$

Equation 10.5, The R squared in which X is the manual forestry assessment data and Y the Kinect data.

The data was visualized in the following scatterplots. Beware the axes contain different scales in each graph, due to the difference in DBH in each plot. Trees not measured were not included in the graphs.




Coniferous
y = 0,9992x
R² = 0,925
RMSE = 0,242536
Average = 68,65
Stdev = 9,20
Measured values (cm)
Observed values (cm)
0
10
20
30
40
50
60
70
80
90
0
50
100


Mixed
y = 0,9578x
R² = 0,935
RMSE = 3,919647
Average = 15,33
Stdev = 7,30
Measured values (cm)
Observed values (cm)
0
5
10
15
20
25
30
35
0
10
20
30
40

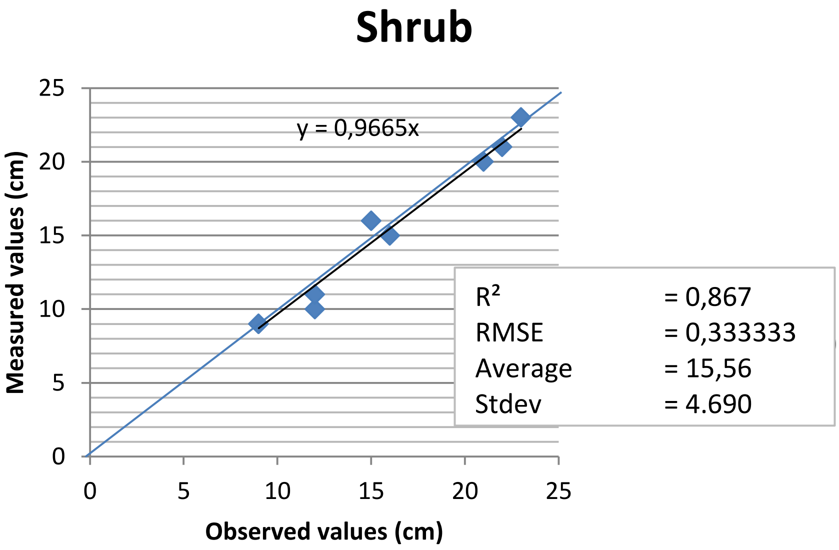


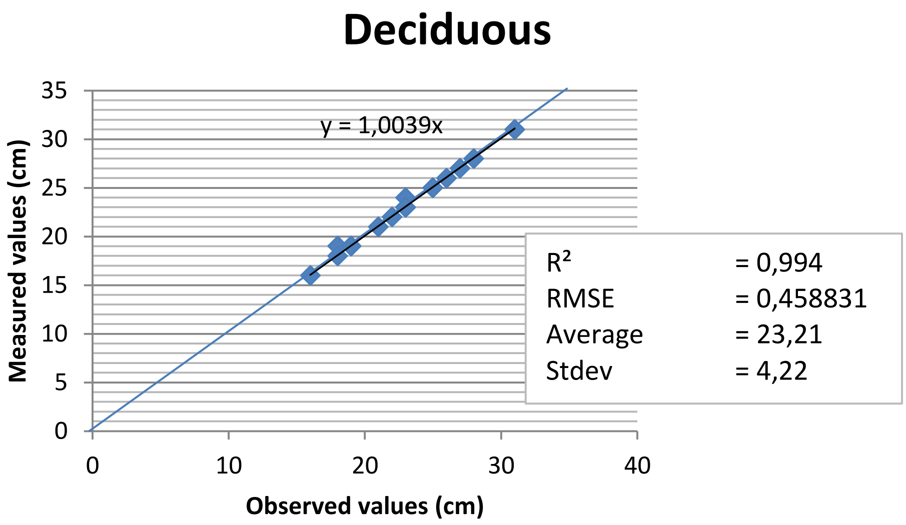
Fig 19. Difference in observed and measured values in diameter for the Microsoft Kinect

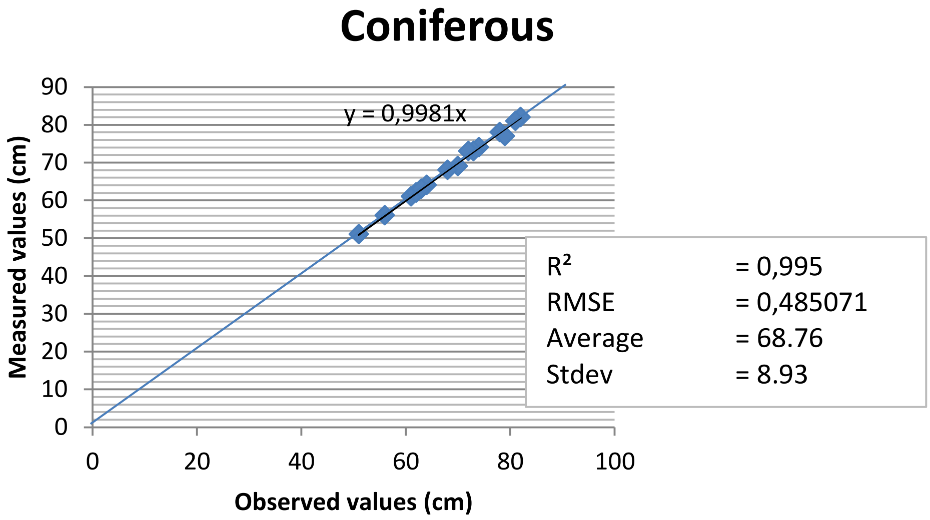
The RMSE and R squared calculations resulted in visualized overview the Kinect abilities to acquire field measurement data. The resulted data proved to be of quality in both the coniferous and deciduous forest stands. Notice also that the axes differ in size as the trees measured have different stand characteristics. The RMSE of the mixed forest stand is higher than the other forest stands. Notice also that the number of trees measured is less because of the accuracy of the Kinect inside forest stands.

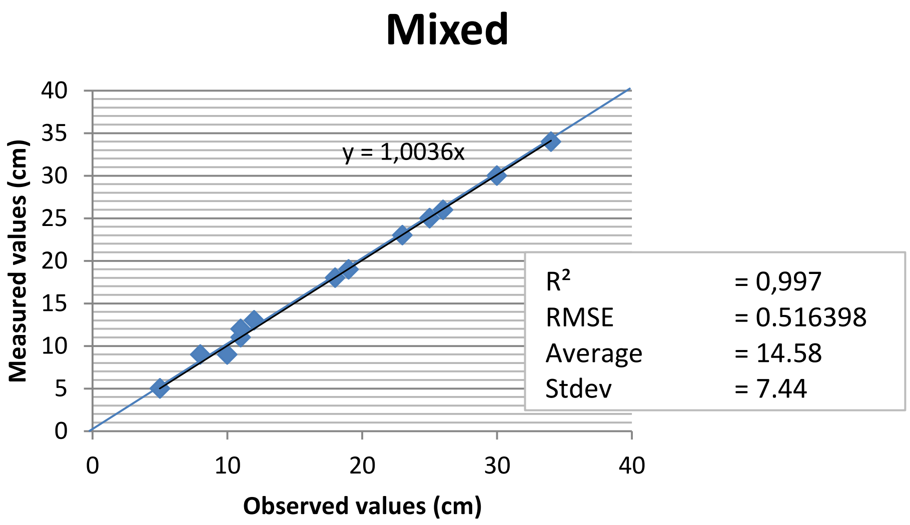
Furthermore it was found that larger trees were more accurately measured than smaller trees, showed in the graphs as a higher level of variation in smaller trees. Because the diameter of the mixed and shrub diameters were usually smaller than productive forest stands trees, the variation is therefore greater.

10.2.2 Diameter quality assessment RIEGL data

The RIEGL data was obtained and processed to acquire the DBH of all trees selected. This resulted in four graphs in which the measured RIEGL values were set out against observed values in centimeter. Also notice the scale on both axes may differ due to difference in height in each forest stand. Trees not measured where not included in the data.


Deciduous
y = 1,0039x
Measured values (cm)
35
30
25
20
15
10
5
0
0
10
20
30
40
Observed values (cm)
R² = 0,994
RMSE = 0,458831
Average = 23,21
Stdev = 4,22


Coniferous
y = 0,9981x
Measured values (cm)
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Observed values (cm)
R² = 0,995
RMSE = 0,485071
Average = 68.76
Stdev = 8.93



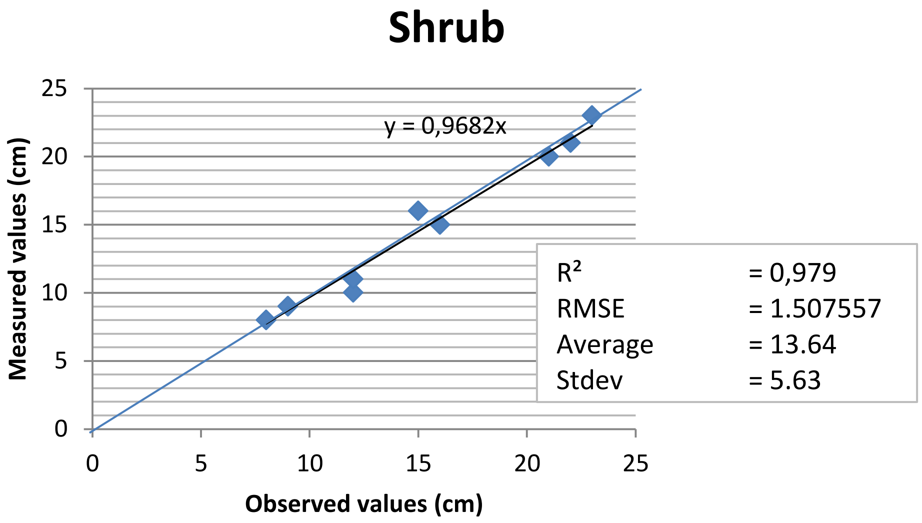


Fig 20. Difference in observed and measured values in diameter for the RIEGL

The RIEGL data showed a good example of tree measurement with a larger and more detailed ranging device. The data showed the RIEGL had no problem accurately measuring the tree DBH inside production forest stands. The only element causing variation was visualized in the mixed and shrub graph causing variation and a higher RMSE. This is caused by difficulty of the RIEGL device to measure through dense vegetation, therefore smaller trees and hidden trees could not be measured correctly, causing the variation.

10.2.3 Diameter data comparison

The data measured for each tree was compared to the RIEGL and Microsoft Kinect data. The data of the Microsoft Kinect showed more variation within the data, and a higher RMSE than the RIEGL data, although the data of the Kinect has accurate results for measuring DBH. The next graph is an accumulation of the RIEGL and Kinect data, which show the difference in measurement. The acquired RMSE values for the entire Kinect and RIEGL dataset are respectively 2,138 and 0,254. This proves that the model with RIEGL data is creating more accurate results than the model with the Microsoft Kinect data.

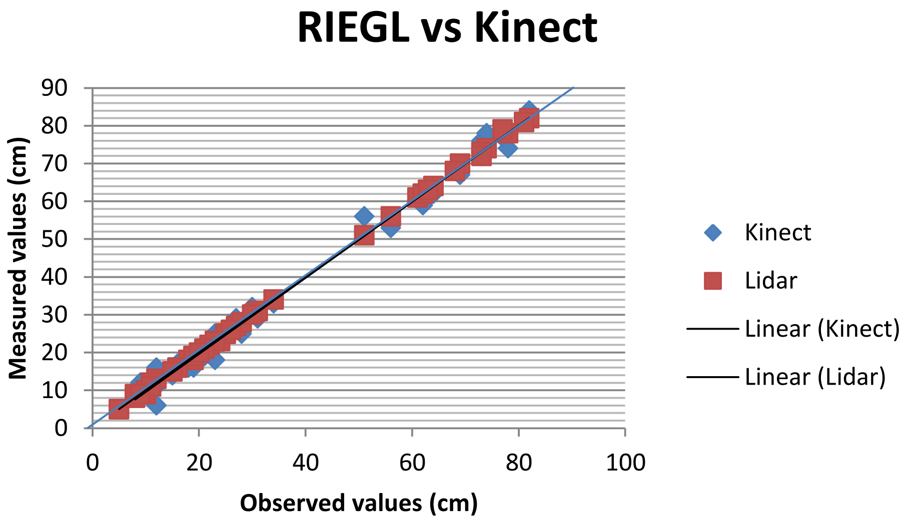


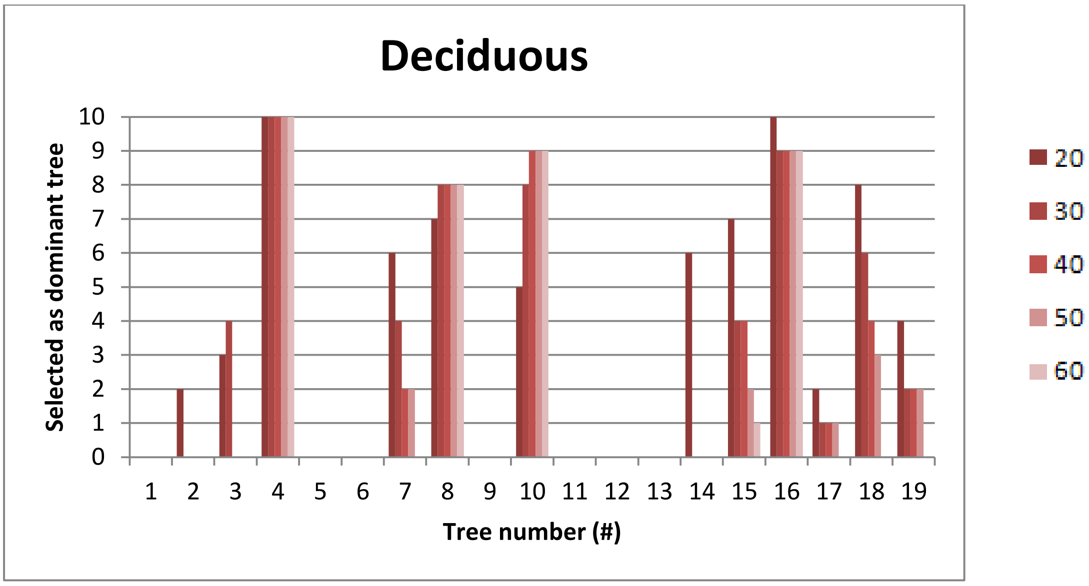
Fig 21. RIEGL versus Kinect data comparison

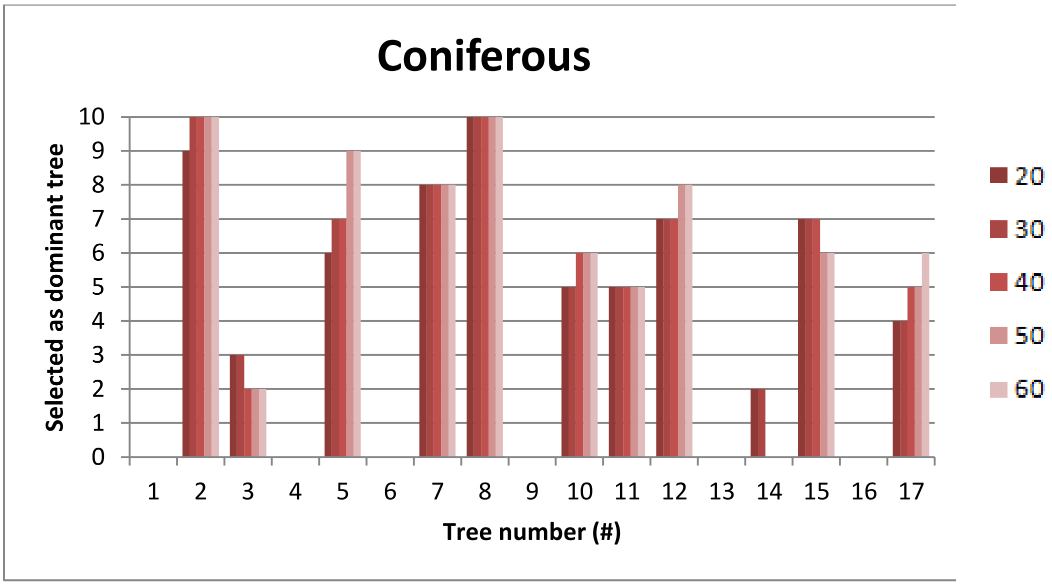
10.3 Data conclusions

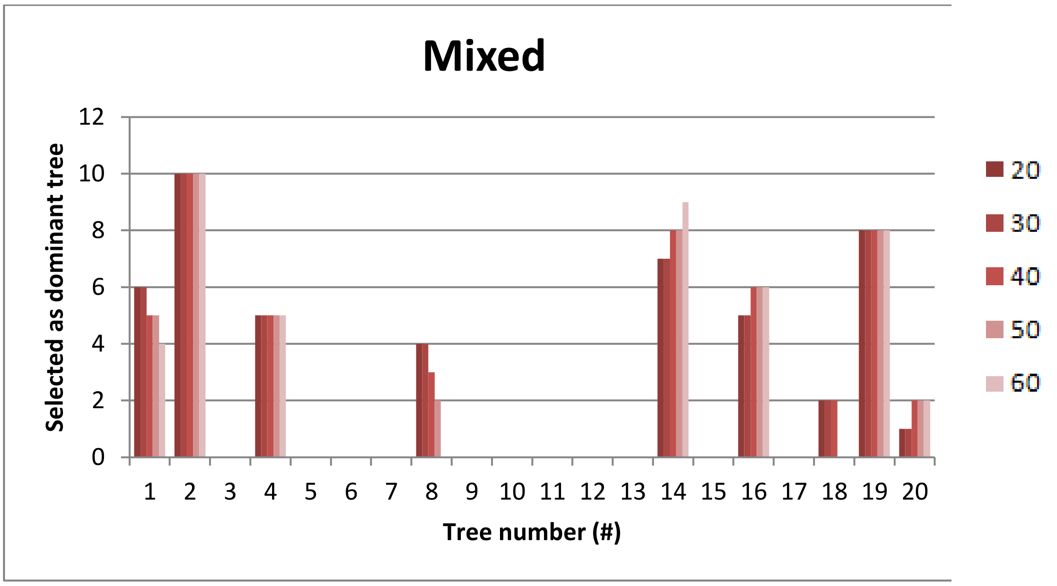
After we combined the quality and quantity test applied to the data, we see overall the RIEGL data has a higher quality and quantity of data. Overall the RIEGL measured more trees and measured these trees more accurately. Especially in systematic forest stands the RIEGL proves to be of higher value than the Microsoft Kinect. However due to the dynamic nature of the Microsoft Kinect, the Kinect was able to measure a more "hidden" trees with greater accuracy.

10.4.1 Manual Forest assessment

The manual forest assessment was performed with 10 forestry student from the department of forest management and nature conservation at Wageningen University. After following the measurement procedure, the results were analyzed, in order to compare those to the results of the Microsoft Kinect and RIEGL data. Below the results of the manual forest assessment were visualized, in which we can see the process of how trees became selected as dominant trees. For each time period, foresters were asked to determine if a tree is dominant.







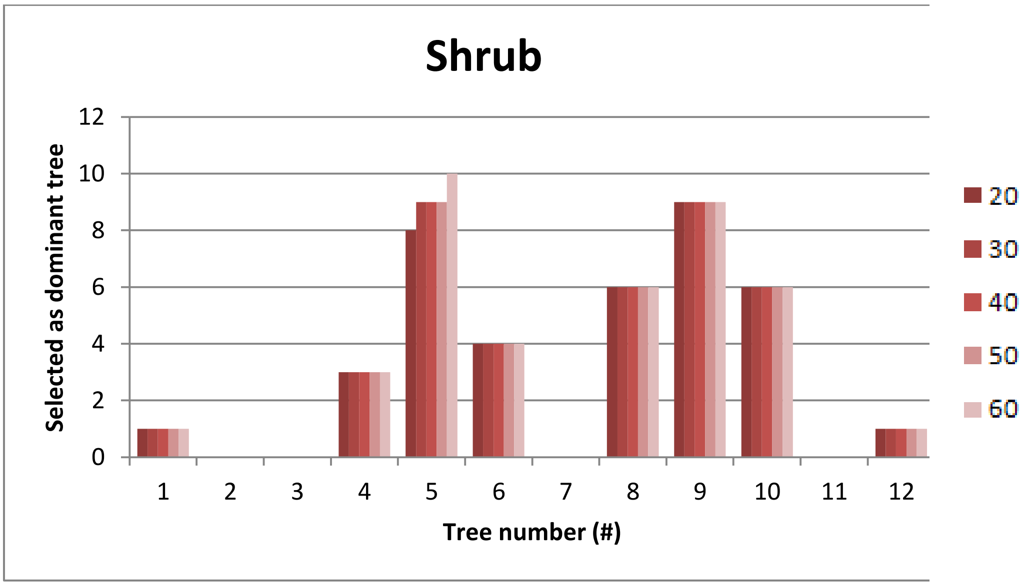


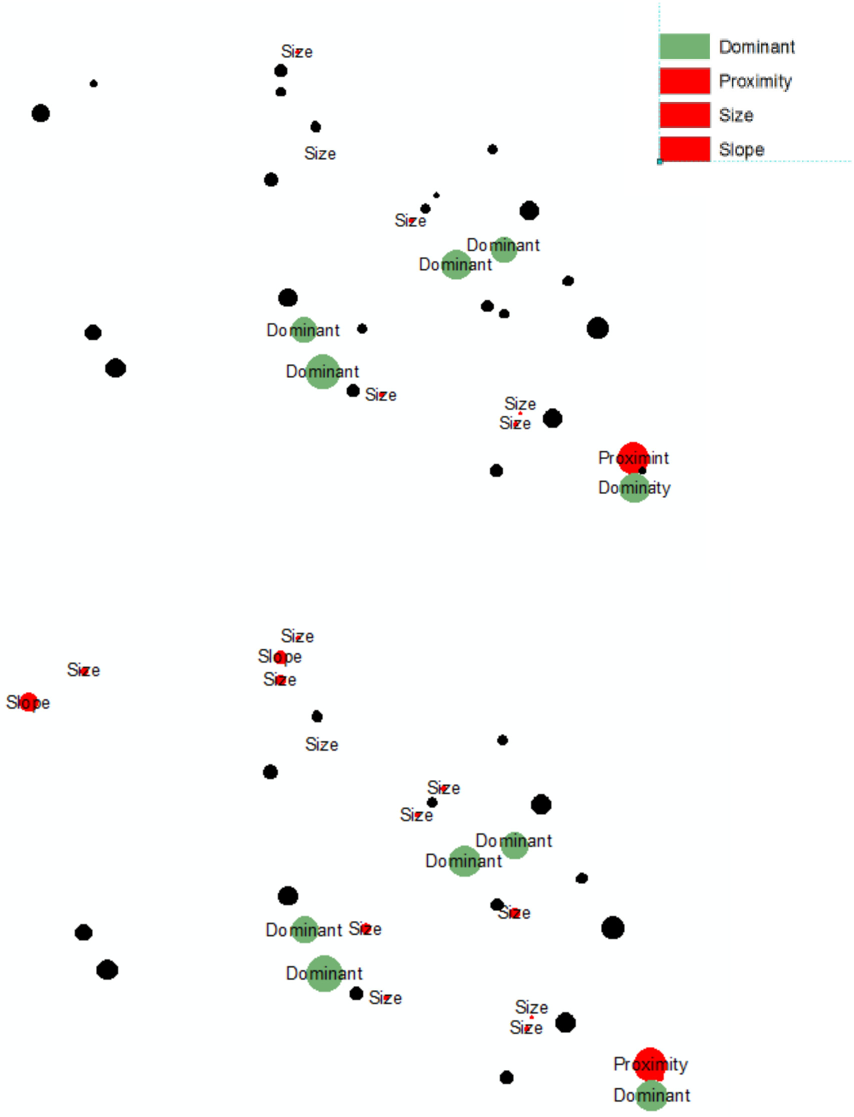
Fig 22. Dominant tree selection process in a deciduous, b coniferous, c mixed and d shrub forest.

The graphs show the MFA choice for each tree to become a dominant tree. The first bar for each tree will give the amount of people selecting that tree to become dominant after the first time interval. The second bar gives an indication after the second time interval. To keep things aligned with the data from the model only the first 60 years were given.

As can be seen, the majority of the trees has been marked either a dominant tree or thinning tree. Only a few trees were marked dominant tree by one half of the forestry students and thinning tree by the other half. Over time, the graph visualized that some foresters change their minds about choosing a particular trees as dominant tree while other trees are selected on a later period as dominant.

10.4.2 Model output for Microsoft Kinect data

Model output for the RIEGL and Kinect was created for each of the forest stands, delivering 8 outputs at the end. The modeling output for the decision making modeling of the deciduous forest stand with Kinect data is visualized in figure 10.6. The model output was constructed as a result of the decision making model. The decision to cut is labeled next to the tree which is being thinned. As can be seen most of the trees are being cut because of small size or close proximity to other dominant trees. The slope as a factor only establish itself in the first or second thinning because after that all ill developed trees are already cut down. Dominant trees are often recognized by their size or far proximity to other trees.



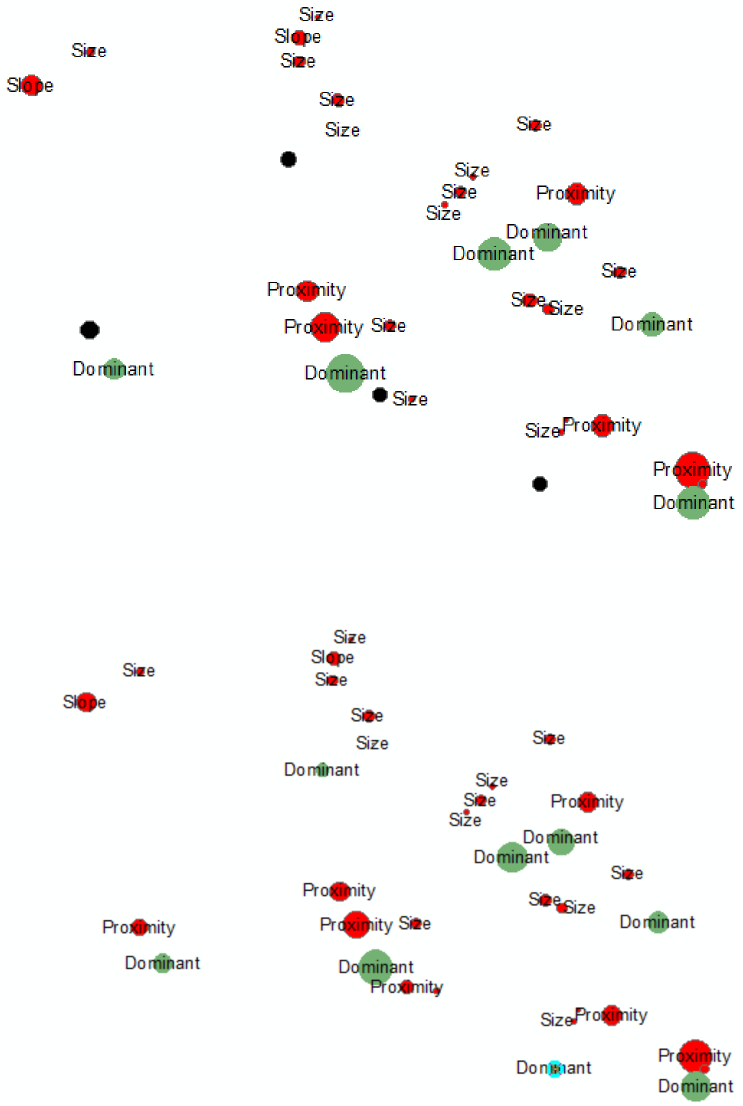


Fig 23. Model output after 10, 20, 40 and 60 years of deciduous stand with label giving indication about thinning criteria.

The data visualized in this image was also set available in data format, which can be compared to the manual forest assessment data. From the data, available in annex I, we calculated the RMSE for each forest stand. The next few graphs show the differences for each of the four forest plots for both RIEGL and Microsoft Kinect based upon the Manual Forest Assessment (MFA); they show the difference between the last phase of the model outcome and the last phase of the Kinect and RIEGL data, thus showing the final dominant trees inside the forest stand.

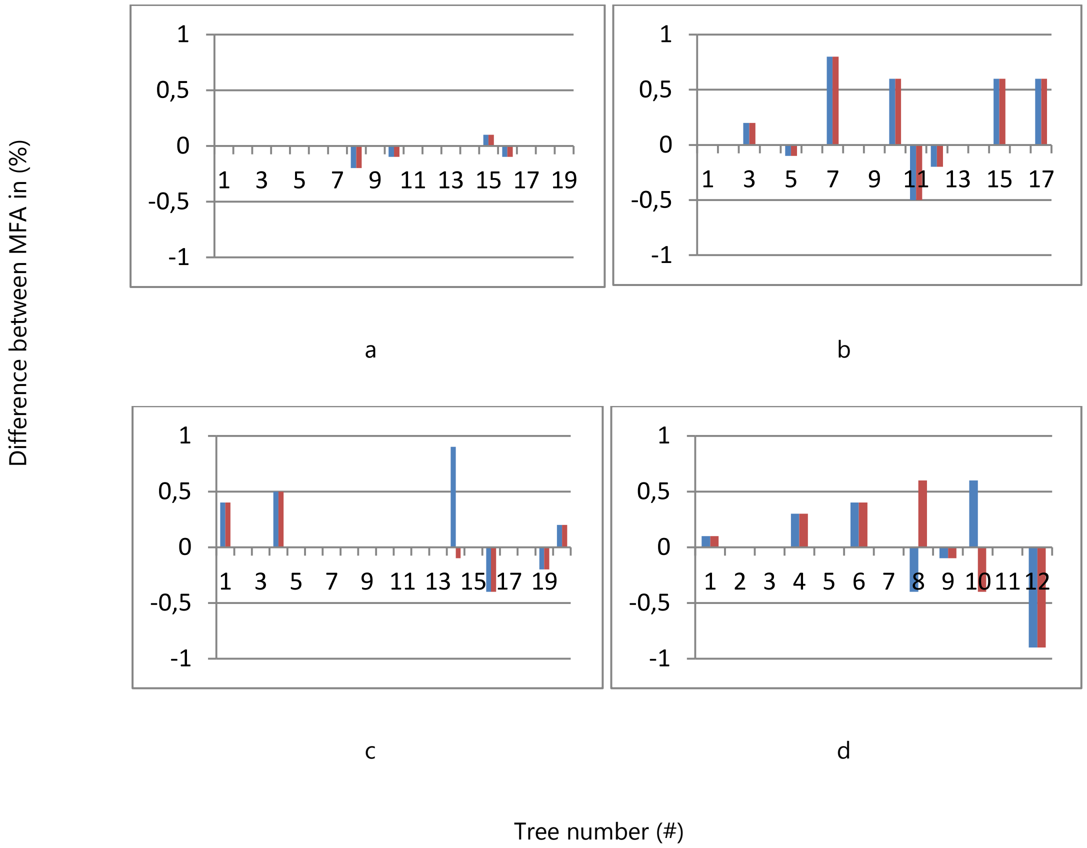


Fig 24. Comparison of the data gather from the MFA and the difference from the MFA data with the in blue (Kinect) and red (RIEGL) data for each of the forest types; a is deciduous, b is coniferous, c is mixed and d is shrub. In which on the y axes 1 stands for 100% difference with the MFA.

The graphs showed the difference of the MFA and the data collected in the Kinect and the RIEGL. In which a 1 indicated that 100% of the foresters chose a different choice of dominance in the MFA then the model did, in the last interval of the decision making model.

As the graph showed, there was almost no variation between the forest manual assessment and the outcome of the model with RIEGL and Kinect data for the deciduous forest stand. The outcome of the MFA and both of the outcomes for the model are close to each other. This means all models are very stable in their outcome.

The coniferous forest stand on the other hand didn’t encounter difference between the RIEGL and Kinect data, but showed a lot of difference with the manual forestry assessment. When we look more closely at the outcome of the manual forestry assessment, shown in graph 10.5, there was already a lot of subjectivity on which of the trees should become the more dominant one. However the Kinect data and RIEGL data based upon the models rules, concluded in the same selected trees.

Because of difference in accuracy and completeness from both the Microsoft Kinect and the RIEGL data, the model ruled in some cases different. The most remarkable being tree nr 14 on mixed forest stand. This tree was selected as dominant tree in the RIEGL model outcome and was thinned in the Microsoft Kinect data. This was caused because of the surrounding tree, number 11, was measured differently in both measurement. Tree number 11 was party hidden therefore measure on only half the diameter, the RIEGL device was measuring.

When combining all of the data and testing the model outcomes using RMSE values, we see that there is no difference between the Deciduous and coniferous RMSE of the RIEGL and Kinect model outcome, however the mixed and shrub forest stand show that the RIEGL has a smaller RMSE and lay therefore close to the MFA. This was due to error such as the example explained in the last paragraph.

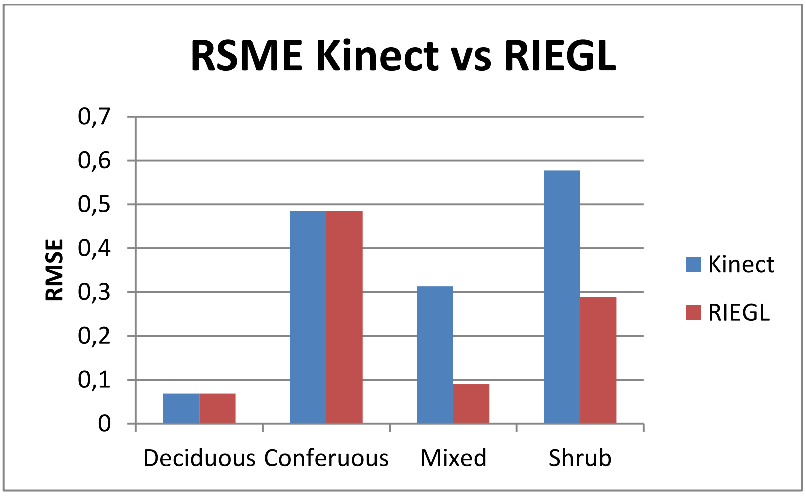


Fig 25. RMSE values of the outcome for the decision making model for both the Kinect and RIEGL data.

When we compare the results of the manual forest assessment to the data analysis of the Microsoft Kinect data and RIEGL data, we can see some great similarity between the datasets. Most of the future trees selected by the manual assessment were also selected as future tree by the Microsoft Kinect and RIEGL data. However the data is more fluctuating in the mixed and shrub forest stands.

10.5 Model output comparison

The outcome of the model was compared to outcome of the manual assessment. The model found that in most cases there is an overlap between the dominant trees selected and chosen in the deciduous forest as well as in the coniferous forest stand. The mixed and shrub trees had lesser results than the production forest types. Although the manual forest assessment and the Kinect data aligned in their choice for potential dominant trees. Basically, because the largest trees in the plot, were selected as the dominant trees. This is also caused by the smaller trees, which were more easily defined as noise cloud.

11. Discussion and recommendations

In this chapter the results of this research are discussed in relation to the concepts discussed in the literature review. Certain elements found in this research will be compared to elements found in empirical data. Hereafter a few recommendations for future research will be given.

11.1 Calibration variation; parameter versus parameter.

Because the Microsoft Kinect is the fastest selling gaming device over the world (BBC, 2011), it was also used in numerous studies for a variety of different scientific fields. Plenty of literature is available describing the characteristics of Kinect measurement techniques and Kinect data. Each of these studies, and for this study nodifferent, start with a calibration phase. Calibration was followed by a number of different techniques and within a variety of software bundles. The outcome of these calibrations, no surprisingly also fluctuated.

In literature a whole scale of different outcomes were found for Kinect parameters and their standard error. When we compare literature studies, we notice the most fluctuating parameter is the range of the Kinect. Of course the range varieties with among others light intensity, but considering most of these experiments described are done indoors, the light intensity should be roughly the same. Where some researchers estimate the maximum range on a minimum 10 meters (Rafibakhsh *et al.* 2012) others estimate this parameter on a whopping 15 meters (Smisek *et al.* 2013).

The differences of the results are implying that for the calibration the results contain variation and are therefore also variable and hard to compare. The range for this study was estimated for about 12 meters in range, varying with different weather and environmental conditions. The Microsoft Kinect has an increased range in a controlled environment. However because the intake of data can be linked to each other, larger areas can be mapped in one take. Further research is needed to investigate the variation in Kinect parameters.

11.2 Calibration variation; 3D checkerboard calibrations.

As mentioned in the last previous part of this chapter, a calibration is needed in order to know the limits of the measurement parameters and to quantify the measurements when described. The depth in this study was measured using a distance towards a plain checker board. The check board method is the most common found calibration method for the Microsoft Kinect found in literature. However some variations can also be found, some of these could increase the calibration results.

The normal checkerboard analysis is performed on a black and white 2D surface. A checkerboard analysis could be improved however by adding depth in the same procedure. This could increase the precision of the calibration. A 3D model can deliver more stable 2D–3D correspondences for camera tracking than depth measurements that are captured on the fly, often eliminating artifacts on the calibration result (Kahn, 2012).

Another form of checkerboard calibration can be performed with an transparent checkerboard. Where a black and white checkerboard is helpful in calibration the RGB sensor, the depth sensor just visualizes a rectangle. Therefore a transparent checkerboard will look a checkerboard to both sensors. With this method RGB and depth can be calibrated in the same time, eliminating calibration errors. Doc-Ok.org, 2013 showed perfect example of perform a

3D checkerboard analysis, another format of a 3D checker board calibration is called a mirroring checkerboard proposed by Schroder et al, 2005.

Because of the high number of calibration methods, it is hard to compare different calibration results. Although some of additions of the original checkerboard analysis as performed in this research could lead to better results, the results of these calibrations cannot be compared to this research. It is therefore needed to establish and regulate a calibration methodology for structured light ranging devices and applications.

11.3 Structured light scanning shortcomings.

Because the Microsoft Kinect was not really designed as a tree measurement device, it has some shortcomings which can disrupt or even corrupt the data acquired. One of the most prominent issues mentioned in the quest to create and develop structured light scanning devices was that it would not work in an open sunny area (Mertz *et al.* 2012). The largest problem these kind of scanner face is the light intensity which masks the light pattern of the devices resulting in corrupt data. However forestry is usually measured under a dense forest canopy, blocking the sunlight from distorting the camera as a whole. This resulted in diminished parameters such as range, described in section 11.1, instead of corrupted data.

Another shortcoming of the Kinect as described by Mertz et al, 2012 is the distortion of data in reflective surfaces creates zero data. Luckily inside the forestry ecosystems, reflective surfaces are difficult to find. Ecosystems with higher moisture content however will be more difficult to measure, because of the higher reflectance values of water. However as mentioned in section 2.2.3, snow and rainy surface may cause corrupted or lacking data (Kutulakos and Steger. 2005). This study was conducted with equal environmental and weather conditions as measurement criteria, therefore all measurements were taken in good weather conditions. More research is needed in order to qualify data taken in different environmental conditions.

Buildin distortions is another shortcoming of the Microsoft Kinect, especially in combination where the depth sensor is paired with the RGB camera. Lens distortions in the depth camera have been a prominent downfall for measurements under certain conditions. A more indepth research on lens distortion was conducted by Khoshelham, 2011. Lens distortion has three large side effects; radial distortion in the RGB camera (1) and camera (2) and depth distortion (3) in the depth camera (Doc-Ok.org, 2013). These three distortions could have intervened in the results and have increased the standard error. However it is believed that the radial distortion in the Kinect sensor is not very significant (Mertz et al, 2012). Further study is needed in order to understand build in camera and sensor distortions.

11.4 Advantages of more advanced forestry models

This research used a number of known parameters for forest modeling. It made use of a simplified forestry model, only taking parameters such as position, DBH, flexure and space between trees in account. Other parameters were dismissed or remained constant. A more complicated model could perform a more realistic approach of the forestry model. Other parameters, which could be obtained from the Microsoft Kinect, could be included for further research. The forestry model could also benefit by adding a financial component to the model.

Two parts of this study couldn't be automatized file type transformation and automatized selection. In order to create an objective function forestry model, these features need to be automatized. There are however a few problems concerning this automatization.

The increase in parameter acquisition also means an increase in file type transformation, which can decrease productivity. This research had use of a variety of file types with different extensions. Li and Hu, 2005 describes this as a result of competitive marketing. However it is also believed that unity in file format for data, reduces the threshold of new consumers to make use of the new software and accelerated research phase.

In this research it has been necessary to manual select the features needed to scan and analyses in ArcGIS. This process can be automatized when the selection procedure in Meshlab was done in ArcGIS. However current computation power at hand was not sufficient to select whole forest stands DBH with ArcGIS. It is therefore recommended that further selection procedure might be developed in the future.

11.5 Subjective manual forestry assessment

Both of the data gathered by the RIEGL and the Kinect was compared with a manual forestry assessment, by feeding this data into a forestry decision making model. However the choices made in this forestry model could compromise the objectivity from the model.

Subjectivity in manual forest assessment is one of the reasons an automatic forestry assessment procedure benefits forestry assessments. In literature, this potential subjectivity was found and described in different format. Collins, (1996) described that the choice of trees within a manual forestry assessment can subjectively change the outcome of a forestry assessment. Other assessments assign weight to specific features in order to label them for future forestry schemes (Assessment, 2005). The weights could be subjectively assigned.

Some researchers go ever further. Mendoza and prabhu, (2000) describe how every choice a forester makes in a forestry assessment is a subjective one. Assessments therefore are a very creative process in which the foresters relay on their creativity, knowledge and experience for their decision making.

Forestry decision making models are more objective in the sense that they function with a given set of rules. The systematic nature of these models allows the model to gain more objective systematic results. The question what is better, a manual creative forestry result or an automated systematic model is one beyond the scope of this research. However both sides can find opportunities and problems.

The comparison of a manual forestry assessment and a systematic decision making model, as done in this research, is therefore an unfair one. Although the results are interesting. Apparently when natural variation is very low, such as in deciduous forest stand, all three assessments are close to each other. But when more dense forest are present, the model varies. Apparently with increase in choice, comes increase in variation.

11.6 Development of ranging applications

Research on structured light scanning device is still in early stage of development. Better and faster devices increase to be sold on the market, and with this new opportunities arise for engineers and scientist to develop applications. Although this research did not really focus on the abilities of the Kinect in general but merely its application in a forestry settings, there are some abilities known which were beyond the scope of this research but could be implemented a forestry assessment.

As Schroder et al, (2005) mentioned, multiple Microsoft Kinect can increase the data quantity within the research. Although the Kinect has a continuous measuring design, in which the device has to move in order to gain more data, more Kinects could increase the measurement design size. One of the Microsoft Kinect limitations is the smaller FOV, which could be increased when more Kinects are added to the same measurement design. However this could also have a few downfalls. Increase processing of data could cause data overloads, which in turn could cause the Microsoft Kinect and connected devices to freeze. Another problem arises when the multiple Kinects are not connected properly, the internal point reference algorithm couldn't handle distorted data and the outcome would be inaccurate. Besides these downfalls, development of a Multikinect measuring design could be beneficial within a forestry setting.

After the success of the Microsoft Kinect on the gaming market, other manufactures begin to develop their structured light based gaming devices. These gaming devices such as the PSDK reference and Asus Xtion pro use a form of structured light coding which is different than the Light Coding of the Microsoft Kinect. A comparison between these devices could have potential for developers to analyze the different results from different devices.

After the Kinect and the Kinect 360, Microsoft developers continue to increase the Kinect product line. The new Microsoft Kinect 720, will give researchers and developers more opportunities for development. Described as the next generation Kinect, this device offers a larger FOV and better accuracy. The main new tool included in the Kinect 720 is the IllumiRoom tool, combining a projector with the Kinect technology to create an even larger FOV (Jones et al. 2013), hypothetically extending the boundaries of forest measuring.

Although this research is focused upon the Microsoft Kinect, we must not forget that the main application of these devices was for the gaming market. Development and research in other fields, even scientific ones, is not in scope of the developers of these devices. I now so happens to be the fact that these devices form the cheapest and accessible method of researching structured light measurement in other fields of study. A device focused on scientific study will allow researchers to develop their own device for their own applications.

11.7 Further research of the Microsoft Kinect in forestry

This thesis has proven that there is a place for the Microsoft Kinect in forestry. However this thesis has only scratched the surface of what is possible within the application of ranging software in the scientific field of forestry. Development of more accurate and powerful structured light ranging applications can one day deliver equal or even better results than LiDAR scanning devices. A number of different paths could be further explored.

Firstly one of the best features of the Microsoft Kinect is its measuring design. The continuous measuring allows the user to reach places hard to measure and analyses by static measuring points. A downfall of this method is that writing points to another device such as a laptop can take a considerable time and when connection to other reference points are lost the Kinect will stop measuring. Successors of the Microsoft Kinect such as the Kinect 720 will have a faster and more stable method of processing data and are therefore faster in their ability to measure forestry data (Jones et al. 2013).

Secondly the model developed in this research, which was used for parameter extracting, used a limited number of parameters. Therefore the model created can be described as a simplified forestry model. For further development this model could be extended towards a more complex forestry model, were more parameters could be added. Additionally these parameters could be fed from external data, therefor limiting the amount of constant factors. It is believed that parameters such as complex structural parameters and even specie determination could be acquired with external data. This would result in a more dynamic and therefore more realistic forestry model. The Microsoft Kinect has ability to measure data precisely from a very small scale, it is therefore believed that advanced parameter extraction must be possible and should be further researched.

Finally, it is sure that a lot of research and development has to be conducted before ranging devices such as the Microsoft Kinect have an actual place in forestry assessments. However the results so far seem promising, with a lot of room for further development.

12. Conclusions

If there is one message coming from this thesis, it is that low budget ranging applications such as the Light Coding technique in the Microsoft Kinect have a place within forestry assessments. The measurement technique developed during this research was able to measure within different forest stands containing different species within different densities.

Ranging applications are low cost techniques which allow structured light patterns to measure depth. This can be beneficial in forestry. The low cost/production ratio can allow small scale foresters to measure forest stands without losing data quality. Ranging devices have therefore found a place within forestry assessments, although the techniques shown in this thesis have merely scratched the surface of what is possible.

This research focused on the questions if a ranging device such as the Microsoft Kinect was capable of delivering accurate and precise forestry data. The data therefore was compared to other data from a RIEGL device measuring with a LiDAR technique. LiDAR devices such as this RIEGL have already earned their stripes within the field of terrestrial forestry management.

The RIEGL device proved to deliver excellent forestry data, capable of extracting almost all individual trees. The Microsoft Kinect on the other hand, had more difficulty measuring tree metrics but still proved to deliver quality data. The data extracted for production forest stands such as monogamous deciduous and coniferous forest stands, were almost identical between the Kinect and the RIEGL. Smaller and denser vegetation showed difficulty for both devices. This is logical because the devices were not equipped to visualize trees through vegetation.

Tree metrics are an important parameter which allows foresters to estimate biomass and because of this revenue for their forest stands. It is therefore vital to gain specific and accuracy tree metric data to gain an as precise estimate of revenue as possible. When the devices were compared in tree metric data such as DBH or flexure of individual trees, the RIEGL showed trouble measuring data within dense forestry patches. Although the Kinect has a lower point density in its measuring technique, its ability to measure continuously proved helpful reaching places hard to measure.

Data wrongfully classified as tree or part of a tree was classified as noise. However it has to be noted the Microsoft Kinect data contained more noise when compared to the RIEGL device. This is also visible in the quality of data, which is higher for the RIEGL than the Kinect device. Noise and noise clouds or clusters will continue to form a problem for ranging systems on all levels. This is one of the largest challenges facing remote scientist in forestry today.

Another question examined if forestry data could be used in decision making models. Decision making models proved helpful to foresters by replacing a manual forestry assessment with an automatic system reducing subjective errors. A small decision making model was build and fed with both RIEGL and Kinect data of the same forest stands. Surprisingly the model demonstrated that there was not much difference between the outcomes of both devices. There was a difference however between the manual forestry assessment and the outcome of the model for both devices. The difference was smallest for the production forest stands and largest for very dense and diverse forestry stands.

The Kinect data proved to measure valuable individual and stand characteristics. Although the data didn’t have the amount of quality in LiDAR devices such as the RIEGL device, it showed that for production stands in various settings, the Kinect could be used for valuable forestry assessments and deliver accurate results. The benefits for small scale foresters therefore are that with low cost equipment and models, they will be able to provide precise measurement data.

Low budget ranging applications such as the Microsoft Kinect have still a long road ahead of them, should they ever want to compete with LiDAR device such as the RIEGL. New technologies in forestry face the challenge of delivering accurate results within a dynamic scientific field. The Kinect and other ranging devices will continue to develop and hopefully have a place in the scientific field of forestry.

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Annex A. Output calibration ROS

```
D =  [-0.3284562758914146, 0.11161239414304096, -0.00021819272592442094, -3.029195446330518e-05]
K =  [430.21554970319971, 0.0, 306.6913434743704, 0.0, 4306569252696676, 227.22480030078816, 0.0, 0.0, 1.0]
R =  [1.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0]
P =  [1.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0, 0.0, 0.0, 0.0, 1.0, 0.0]
# oST version 5.0 parameters



[image]

width
640

height
480

[narrow_stereo/left]

camera matrix
430.212350 0.000000 301.691343
0.000000 428.532693 227.22500
0.000000 0.000000 1.000000

distortion
-0.237586 0.111312 -0.001218 -0.000090 0.0000

rectification
1.000000 0.000000 0.000000
0.000000 1.000000 0.000000
0.000000 0.000000 1.000000

projection
1.000000 0.000000 0.000000 0.000000
0.000000 1.000000 0.000000 0.000000
0.000000 0.000000 1.000000 0.000000
```

Annex B. Calibration depth calibration

Calibration results from depth calibration.

Distance [m]	0,6	0,8	1	1,2	1,4	1,6	1,8	2	2,2	2,4	2,6	2,8	3	3,5	4
Reading	544	681	756	810	850,0	878	902,5	921,5	937	949,5	959,5	969,5	978	993	1005
Inv. Distance [1/m]	1,67	1,25	1	0,83	0,71	0,63	0,56	0,5	0,45	0,42	0,38	0,36	0,33	0,29	0,25

Table B1. Calibration results

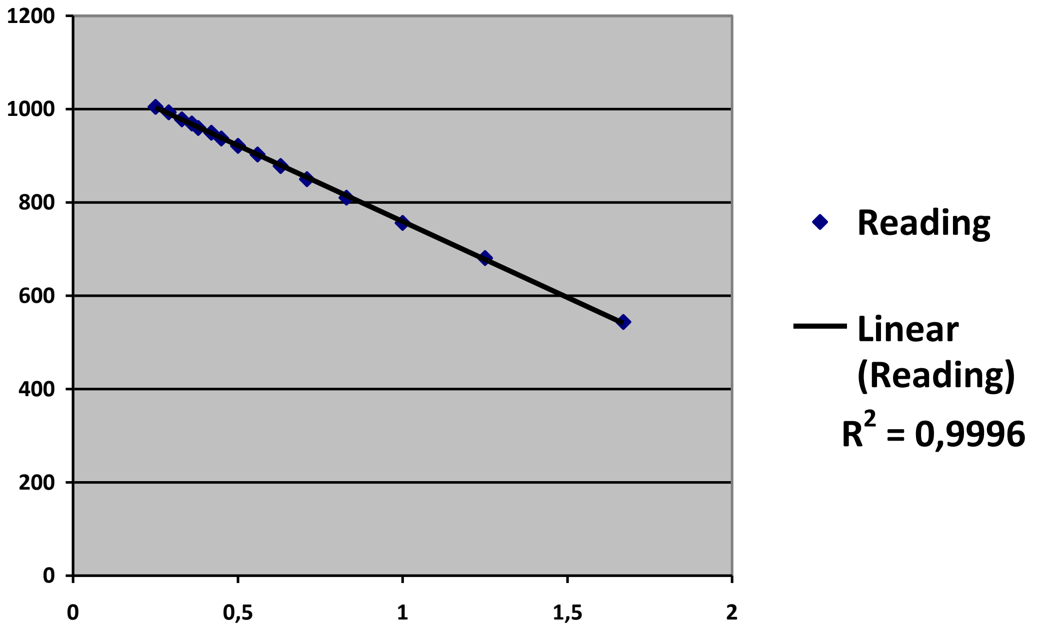
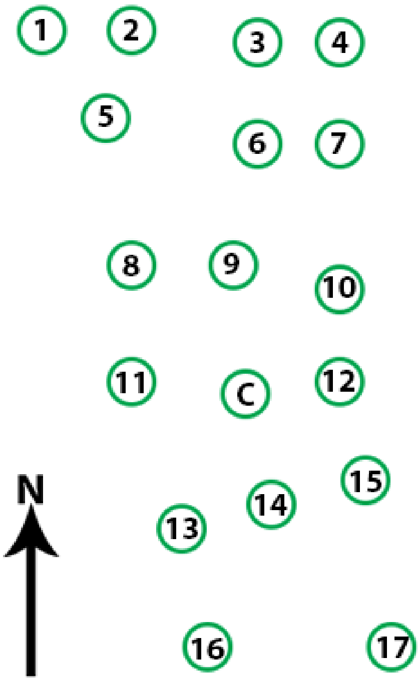


Fig B1. Reading of calibration measurement of middle pixel verse the inverse distance.

Annex C. Example Field survey forestry stand coniferous



Type: Coniferous

Date: 15-01-2013

Tree number: 12

Tree species: *Pseudotsuga menziesii*

Timespan: 80 years

10 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

20 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

30 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

40 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

50 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

60 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

70 years

Tree Nr	Save/Cut/None	Tree Nr	Save/Cut/None
1		10	
2		11	
3		12	
4		13	
5		14	
6		15	
7		16	
8		17	
9		C	

<table>
<tr>
<td>80 years</td>
<td>
<table>
<tr><td>Tree Nr</td><td>Save/Cut/None</td><td>Tree Nr</td><td>Save/Cut/None</td></tr>
<tr><td>1</td><td></td><td>10</td><td></td></tr>
<tr><td>2</td><td></td><td>11</td><td></td></tr>
<tr><td>3</td><td></td><td>12</td><td></td></tr>
<tr><td>4</td><td></td><td>13</td><td></td></tr>
<tr><td>5</td><td></td><td>14</td><td></td></tr>
<tr><td>6</td><td></td><td>15</td><td></td></tr>
<tr><td>7</td><td></td><td>16</td><td></td></tr>
<tr><td>8</td><td></td><td>17</td><td></td></tr>
<tr><td>9</td><td></td><td>C</td><td></td></tr>
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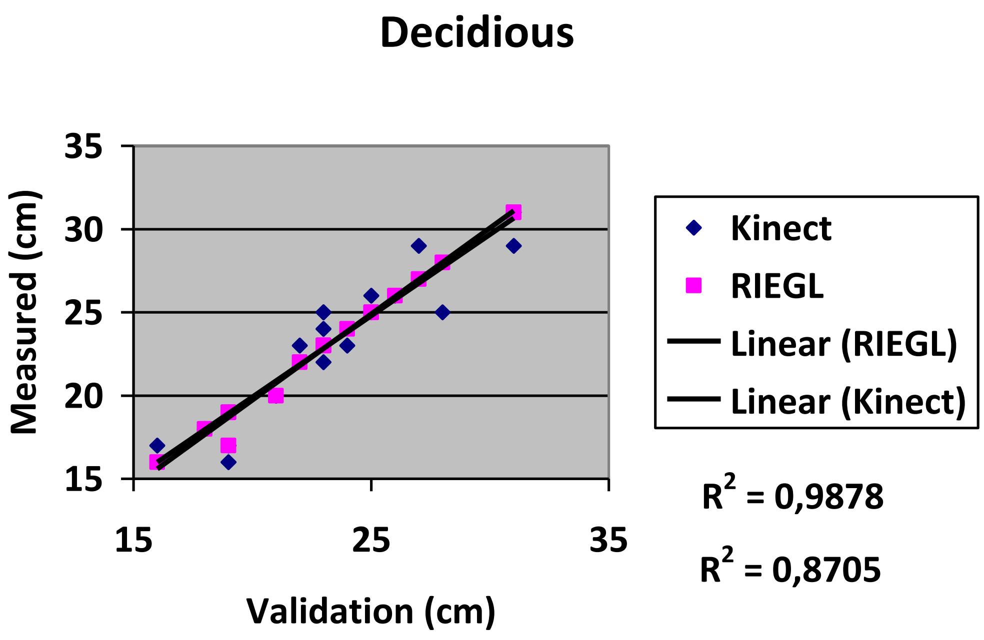
</table>

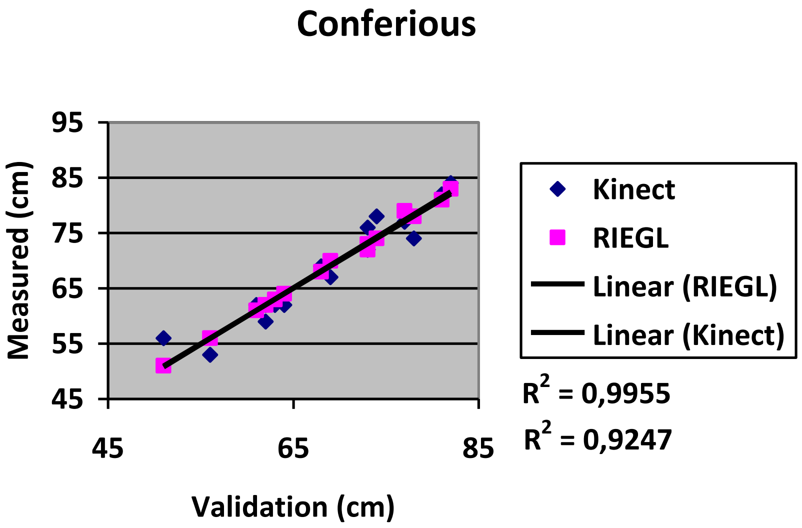
Annex D. Data of forestry measurement assessment

Decidiious									
	Measurment	Kinect	Tree Measurement	Difference	Real error	RIEGL	Tree Measurement	Difference	Real error
Trees									
1	23	22	1	1	1	23	1	0	0
2	25	25	1	0	0	25	1	0	0
3	23	25	1	-2	2	23	1	0	0
4	31	29	1	2	2	31	1	0	0
5	19	16	1	3	3	17	1	2	2
6	18	18	1	0	0	18	1	0	0
7	24	23	1	1	1	24	1	0	0
8	26	26	1	0	0	26	1	0	0
9	27	29	1	-2	2	27	1	0	0
10	28	25	1	3	3	28	1	0	0
11	31	31	1	0	0	31	1	0	0
12	16	17	1	-1	1	16	1	0	0
13	19	19	1	0	0	19	1	0	0
14	21	20	1	1	1	20	1	1	1
C	22	23	1	-1	1	22	1	0	0
16	23	25	1	-2	2	23	1	0	0
17	23	24	1	-1	1	23	1	0	0
18	25	26	1	-1	1	25	1	0	0
19	19	17	1	2	2	19	1	0	0
			1		23		**1**		3



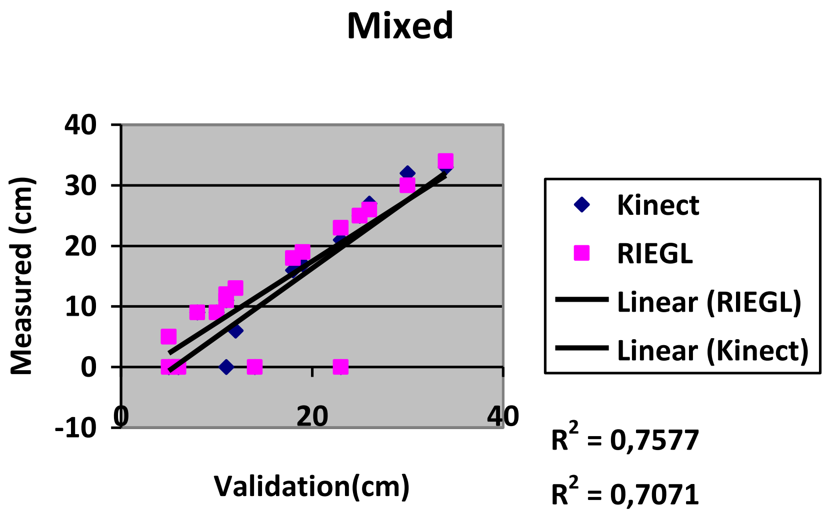
Conferious									
	Measurments (cm)	Kinect (cm)	Tree Measurement	Difference	Real error	RIEGL	Tree Measurement	Difference	Real error
Trees									
1	61	62	1	-1	1	61	1	0	0
2	82	84	1	-2	2	83	1	-1	1
3	73	76	1	-3	3	73	1	0	0
4	51	56	1	-5	5	51	1	0	0
5	64	62	1	2	2	64	1	0	0
6	62	59	1	3	3	62	1	0	0
7	74	78	1	-4	4	74	1	0	0
8	81	82	1	-1	1	81	1	0	0

9	62	62	1	0	0	62	1	0	0
10	69	67	1	2	2	70	1	-1	1
11	68	69	1	-1	1	68	1	0	0
12	73	72	1	1	1	73	1	0	0
13	78	74	1	4	4	78	1	0	0
14	77	77	1	0	0	79	1	-2	2
C	73	72	1	1	1	72	1	1	1
16	56	53	1	3	3	56	1	0	0
17	63	62	1	1	1	63	1	0	0
			1		34		**1**		5



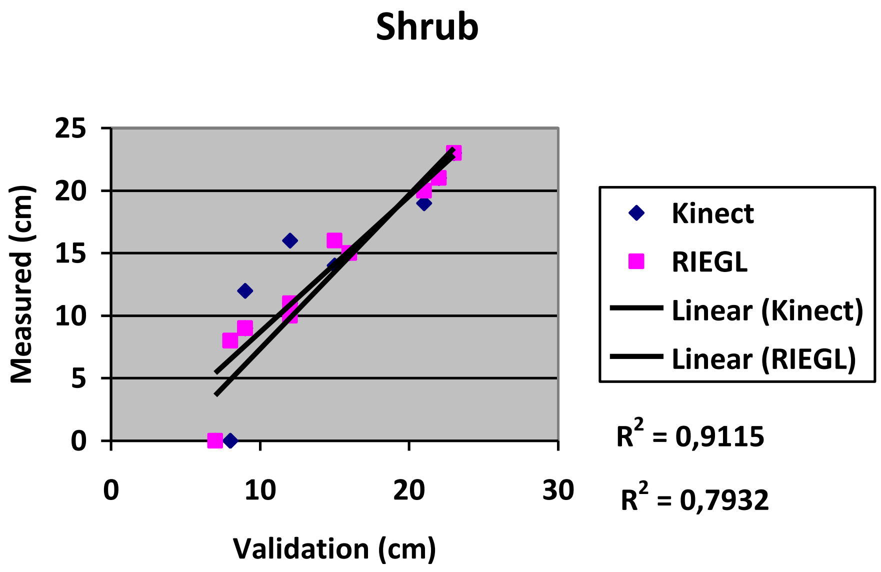
Mixed									
	Measurment	Kinect	Tree Measurement	Difference	Real error	RIEGL	Tree Measurement	Difference	Real error
Trees									
1	30	32	1	-2	2	30	1	0	0

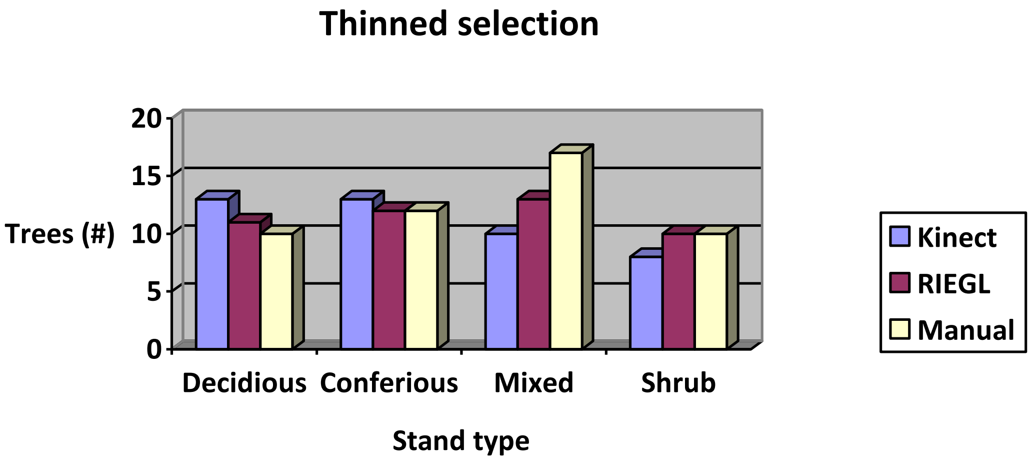
2	34	33	1	1	1	34	1	0	0
3	25	25	1	0	0	25	1	0	0
4	10	9	1	1	1	9	1	1	1
5	5	0	0	5	0	5	1	0	0
6	6	0	0	6	0	0	0	6	0
7	5	0	0	5	0	0	0	5	0
8	23	21	1	2	2	23	1	0	0
9	14	0	0	14	0	0	0	14	0
10	5	0	0	5	0	5	1	0	0
11	12	6	1	6	6	13	1	-1	1
12	11	11	1	0	0	11	1	0	0
13	11	0	0	11	0	12	1	-1	1
14	18	16	1	2	2	18	1	0	0
15	6	0	0	6	0	0	0	6	0
C	25	25	1	0	0	25	1	0	0
17	23	0	0	23	0	0	0	23	0
18	19	17	1	2	2	19	1	0	0
19	26	27	1	-1	1	26	1	0	0
20	8	9	1	-1	1	9	1	-1	1
			0,6		18		**0,75**		4

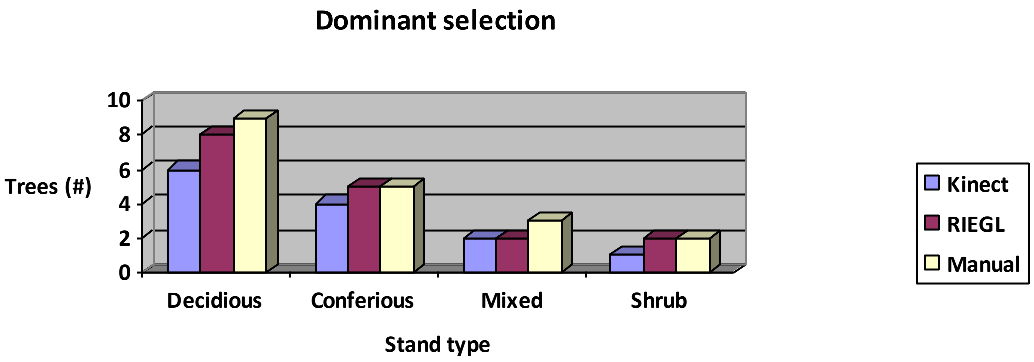


Shrub									
	Measurment	Kinect	Tree Measurement	Difference	Real error	RIEGL	Tree Measurement	Difference	Real error
Trees									
1	12	16	1	-4	4	10	1	2	2
2	8	0	0	8	0	8	1	0	0
3	9	9	1	0	0	9	1	0	0
4	15	14	1	1	1	16	1	-1	1
5	23	23	1	0	0	23	1	0	0
6	12	11	1	1	1	11	1	1	1
7	7	0	0	7	0	0	0	7	0
8	16	15	1	1	1	15	1	1	1
9	22	21	1	1	1	21	1	1	1
10	21	19	1	2	2	20	1	1	1
11	8	0	0	8	0	8	1	0	0
12	9	12	1	-3	3	9	1	0	0

	0,75	13	0,92	7


Shrub
Measured (cm)
25
20
15
10
5
0
0
10
20
30
Validation (cm)
Kinect
RIEGL
Linear (Kinect)
Linear (RIEGL)
R² = 0,9115
R² = 0,7932


Thinned selection
Trees (#)
20
15
10
5
0
Decidious
Conferious
Mixed
Shrub
Stand type
Kinect
RIEGL
Manual


Dominant selection
Trees (#)
10
8
6
4
2
0
Decidious
Conferious
Mixed
Shrub
Stand type
Kinect
RIEGL
Manual

Annex F1. Documentation on the installation Kinect on different OS.

The Kinect can be installed on different Operating Systems (OS). The following annex gives documentation how the Kinect drivers and middleware was installed on two Operating Systems. In order to let the Microsoft Kinect communicate with an Operating System (OS) on a PC, it is necessary to install one or more drivers. Drivers control and operate the plugged in device. The Kinect drivers are openly distributed and supported from Microsoft.

Installing Microsoft Kinect to a Personal Computer (PC)

The Microsoft Kinect consists out of the device and a special adapter which connects to a USB 2 port. However the Kinect does not work with a common USB 2 port because its power consumption by the motor part is slightly higher (ULE Robotics Group, 2013). The Kinect therefore needs a special adapter which is included in device. Newer models do not require an adapter and can directly be charged using a laptop.

Configuring Microsoft Kinect on a Windows OS

After installation of this Kinect for Windows SDK and the Developer Toolkit (Microsoft 2, 2013) the Microsoft Kinect can be plugged in.

Another method is installing the The Zigfu development kit included a number of the following packages; OpenNI, SensorKinect and Nite. All of these packages (or middleware) were focused on controlling and operating the Microsoft Kinect on a Windows platform. The middleware is also available in number of other software packages. These packages are bundled in one software package called Zigfu (Zigfu.com, 2013). On the website there is an option to also include the drivers in one installation sequence.

> **OpenNi** (1) has been created by the Open Natural Interaction (Open NI, 2013). In this research OpenNI 1.5.2.33 was used as well as OpenNI 2 in the Zigfu package.
>
> **SensorKinect** (2) In this research SensorKinect 5.1.025 was used
>
> **Nite** (3) In this research Nite 1.5.2.21 was used.

After installation of these middleware, the device is ready for use.

Configuring Microsoft Kinect at an Ubuntu 11.0

The best method (Vermeulen J, 2012) of installing the Kinect drivers on the Ubuntu 12.0 (also working on Ubuntu 11.0), was to install the official packages of libfreenect (Libfreenect, 2013):

```
$ sudo apt-get install freenect
```

ROS as well as PCL provide packages which include preinstalled drivers for Ubuntu. For example installing drivers with the ROS package, after following the installation tutorials (ROS 4,5, 2013) can be done giving the following code:

```
sudo apt-get install ros-electric-openni-kinect
```

Annex G Checkerboard calibration

A checkerboard analysis was performed in the ROS development kit to research the depth and RGB data. Although this research focusses heavily on depth and not so much on RGB, it will show a number of methods in order to calibrate the RGB values as well. Kinect calibration software is also available as other numerous software packages on multiple Operating Systems.

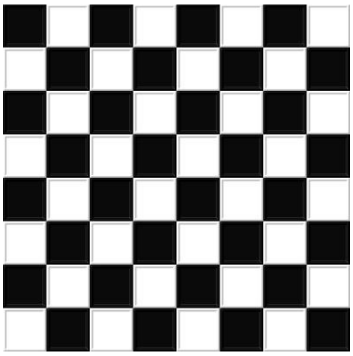


Figure 1. Checker board example

This analysis was performed using a checkerboard analysis. This analysis uses the known distance on a checker board to analyses the precise distance anywhere else on the same distance. This method creates a calibration for the color and contrast sensors of the Microsoft Kinect.

RGB calibration

The RGB calibration was performed using ROS on the Ubuntu 11.0 OS. In ROS the following example code opened up the calibration window.

```
rosrun camera_calibration cameracalibrator.py --size 8x6 --square 0.108 image:=<input> camera:=<camera path
input>
```

Hereafter the Microsoft Kinect could be calibrated by moving the checkerboard in front of the camera and wait until the checkerboard is calibrated. The process of calibration is done by selecting number of "tie points" in the image manually and storing this in the calibration software. A successful checkerboard analysis in Diamond back will result in an image where real world straight edges will appear straight in the corrected image. Finally after calibration the output can be read in the terminal (ROS 6, 2013). An example output has been placed in Annex 1.

Depth Calibration

Successful calibration for different distances was obtained and measured. These output files were collected and hereafter each center pixel was read and measured. This resulted in the following regressed data in which the depth output data appears to be linearly proportional to the inverse of the distance to the object. The table outcome can be found in Annex B. The regression constants are needed to automate the calibration process in RGBDEMO 0.7.0.

Introduction to RGBDemo 0.7.0

RGBDemo 0.7.0 is part of the open source RGBDemo franchise software developed by Nicolas Burrus (Burrus, 2012), that aims to provide a simple GUI and toolkit to analyze and capture Kinect data. This software franchise was used to capture and project data in de field. The software is based upon standalone libraries such as the Netsk library. Nestk is the core library supported by several smaller libraries. It was created to integrate the existing cmake-based software more quickly. The library is based upon Point Cloud Library, OpenCV en QT for the visualization. The software is divided in several demo programs. The different demo programs enable the user to grab Microsoft Kinect data. Calibrate the data and automatically create 3D modeling scene with markers. It can hereafter be exported in a number of file types such as .ply.

Calibration using RGBDemo 0.7.0

Calibration in the RGBDemo 0.7.0 software suite is done using stereo calibration. Raw depth data is collected in integer varying between 0 and 2047. These can be transformed into depth parameters in meters using the method created during the ROS Kinect project (ROS, 2012). The calibration for the initial depth can be computed using the following python code (Burris, 2012). In which X and Y are the values computed with the ROS Kinect project method:

Depth calibration in RGBDemo through python

```
float raw_depth_to_meters(int raw_depth)
{
  if (raw_depth < 2047)
  {
   return 1.0 / (raw_depth * X + Y);
  }
  return 0;
}
```

The color calibration was performed in a similar method.

Annex H PCL script noise reduction

The Point cloud Library noise reduction was performed on A Ubuntu 11.0 OS. \the moving least squares temples used in this analysis can be seen below.

PCL MovingleastSquares as .cpp

```
#include <pcl/point_types.h>
#include <pcl/io/pcd_io.h>
#include <pcl/surface/mls.h>

int
main (int argc, char** argv)
{
  pcl::PointCloud<pcl::PointXYZ>::Ptr cloud (new pcl::PointCloud<pcl::PointXYZ> ());
  pcl::io::loadPCDFile ("bun0.pcd", *cloud);

  pcl::search::KdTree<pcl::PointXYZ>::Ptr tree (new pcl::search::KdTree<pcl::PointXYZ>);

  pcl::PointCloud<pcl::PointNormal> mls_points;

  pcl::MovingLeastSquares<pcl::PointXYZ, pcl::PointNormal> mls;
  mls.setComputeNormals (true);

  mls.setInputCloud (cloud);
  mls.setPolynomialFit (true);
  mls.setSearchMethod (tree);
  mls.setSearchRadius (0.025);
  mls.process (mls_points);
  pcl::io::savePCDFile ("<output>", mls_points);
}
```

This script is based upon the example script shown in the PCL documentation (PCL 2, 2013).

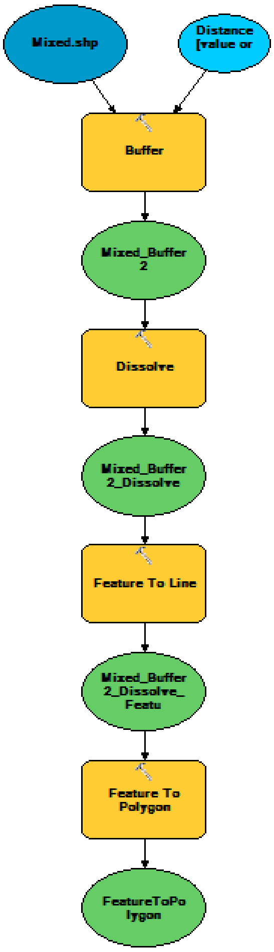
Annex I Grouping scripts

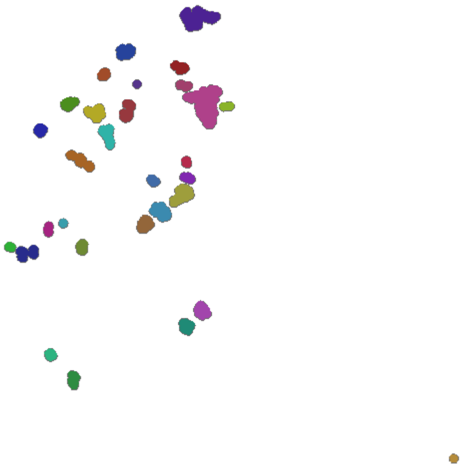
The grouping of trees was done following the process described below. In this annex the grouping code snippets will be displayed folowed by their graphic outcome. A buffer procedure in the model was performed using the folowing code snippet;

Buffer procedure for points in ArcGIS through Python plugin

```
arcpy.Buffer_analysis("<input>", "<output>", "100 Feet", "FULL", "ROUND", "LIST", "Distance")
arcpy.Dissolve_management("<input>", "<output>")
arcpy.FeatureToLine_management("<input>", "<output>,"0.01 Meters","ATTRIBUTES")
arcpy.FeatureToPolygon_management("<input>", "<output>","","NO_ATTRIBUTES","")
```

Resulting in the following model and output:



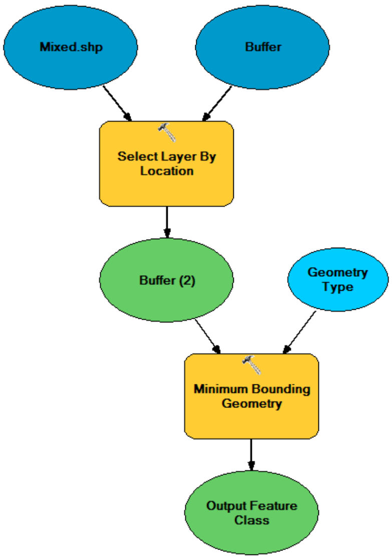


Model and output for selection procedure

The tree features were all buffered, but as can be seen some features were clustered together. Another approach used in this research was to aggregate the point cloud to a polygon feature.

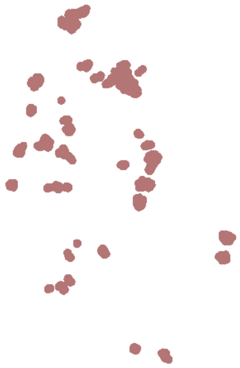
Polygon aggregation in ArcGIS through Python plugin

```
in_point_features = "<input features"
out_feature_class = "<output features>"
aggregation_distance = "<aggregation distance>"
arcpy.AggregatePoints_cartography(in_point_features, out_feature_class, aggregation_distance)
```



Creating convex hull

As can be seen below both methods give valid results. After visual inspection of a number of plots, the first strategy was chosen.



Grouping points and aggregating points

A minimum bounding geometry was used in python to gain a number of groups representing the tree features. The code snippet representing the layout for this is shown below.

```
arcpy.MinimumBoundingGeometry_management("<input>", "<output>",  "<shape>", "NONE")
```

Annex J. File type transformations

Using a large number of software packages on two operating systems with a number of different libraries it is essential to be able to export and import files in each sequential software package.

Ply to Shp

In order to transform ply files (Polygon File Format) to .shp files (Shapefile) a number of steps are needed. The most direct method used in this research is to transform the .ply files in xyz (rgb) stored files and transforming these manually to a csv file. This can be done by manually editing the suffix of the filetype and removing any excessive lines of code describing the data above the data inside the file. Additionally an ID needs to be manually edited in order for a CSV file to be modified in ArcGIS. This can be done using software packages such as Open Office or Microsoft Excel. However this last one, has a restriction on the amount of incoming data rows.

The csv file can be opened in ArcGIS 10.0. In ArcScene and ArcMap 10.0 it is possible to create a shp file, by importing the CSV file and importing XYZ data. The first three rows of the data were selected as x, y and z data respectively. Besides manual transformation there are a couple of software packages on the market automizing this process.

LAS to Shp

The RIEGL files were delivered in a LAS format and needed to be transformed to SHP file format. This was accomplished by using the LAS to multipoint tool after creating a new LAS file in ArcSCENE and hereafter exporting the file to a SHP file format. This code snippet was imported in the model as follows:

```
arcpy.CreateFileGDB_management("<output path>", "<output>")
arcpy.CreateFeatureDataset_management("<path to GDB>", "<input name>", "<input>")
```