Mendel University in Brno

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Accuracy and reliability analysis of timber measurement and scaling using harvesters

DIPLOMA THESIS

2017 Bc. Ilari Ollila

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Abstract

Name: Ilari Ollila

Topic: Accuracy and reliability analysis of timber measurement and scaling using harvesters

Abstract: At the start of millennia harvesters in forestry have gained popularity for their productive and accurate timber processing. However the accuracy of harvester measurement and overall reliability is often in question and hot topic in forest technology, as it is directly responsible for economical profits of the machine. As harvester's timber measurement is affected by various factors both internally and externally, the influence level of these factors needed practical approach. In the view of this, aim of this analysis was directed to discover the factors and characteristics that are essential to harvester's timber measurement

Target of this analysis is divided in to practical field measurements and harvester simulator experiments. In the field measurements small number of trees were measured with various measurement methods, which are used in the professional field of forestry. For harvester simulator experiments, number parameters in the computer system were chosen, that are linked to timber measurement and modified based on their individual characteristics. Results for both field measurements and harvester simulator experiments were processed and analyzed to see which had the most essential effect on the measurement accuracy and reliability, and what other discoveries it might produce.

Field measurement data analysis discovered that 3D scanner and image analysis produced the most accurate measurement results, and harvester underestimated the tree volume data in most of the assortments. Other notion was that image analysis over measured some tree stem bases, that had over expanded butt part. Simulator parameter experimentation led to the discovery, that price type and diameter base curve had the most influence on the timber volume estimation, while other experimented parameters produced less data change after their modification. Also some parameter were restricted by other parameters from producing any possible discoveries.

Key words: Harvester, timber measurement, harvester simulator, 3D scanner, computer system parameter

Abstrakt

Jméno: Ilari Ollila

Nazév diplomové práce: Accuracy and reliability analysis of timber measurement and scaling using harvesters

Abstrakt: Na počátku tisíciletí se lesnické harvestory staly čím dál oblíbenějším mechanizačním prostředkem díky vysoké produktivitě a přesnosti zpracování dřeva. Nicméně přesnost měření harvestory je často zpochybňována a je opakujícím se tématem debat v lesnických kruzích, protože přímo ovlivňuje ekonomickou výnosnost stroje. Vzhledem k tomu, že je harvestorové měření ovlivňováno jak vnitřními, tak vnějšími vlivy, je nutné vyhodnotit míru těchto faktorů prakticky. Proto je cíl této analýzy zaměřen na určení těch vlivů a charakteristik, které jsou nezbytné k provedení měření dřeva s pomocí harvestoru.

Cíl této práce je rozdělen na terénní měření a experimenty v harvestorovém simulátoru. Terénní práce obsahovala měření malého počtu stromů různými metodami používanými v lesnické praxi. Experimenty za použití simulátoru harvestoru zahrnovaly výběr několika výpočetních parametrů souvisejících s měřením dřeva a jejich pozměnění v závislosti na individuálních vlastnostech. Výsledky obou měření, jak terénního, tak simulovaného, byly zpracovány a vyhodnoceny se záměrem určit který faktor měl nejzásadnější vliv na přesnost a spolehlivost a eventuálně daší možná zjištění.

Analýza dat z terénního měření určila, že nejspolehlivější metodou měření byla 3D měření spolu s obrazovou analýzou snímků a že harvestor ve většině měření podhodnocoval objem dříví. Dalším zjištěním bylo nadhodnocování měření kmenů pomocí analýzy snímků v případě zbytnění oddenku. Experimenty v prostředí simulátoru bylo zjištěno, že typ ceny a křivka průměrů kmene měly největší vliv na odhad objemu měřeného dříví, zatímco ostatní parametry měly na změnu výsledných dat menší vliv. Některé z parametrů byly omezeny jinými faktory a neumožňovaly tak získání dalších výsledků.

Klíčová slova: dříví harvestory, měření dřevo, harvestor simulátor, 3D scanner, parametr počítačový system

List of Abbreviations

CTL – Cut-to-length

GPS – Global Positioning System

O.B.C.S – On Board Computer System

XML – Extensive Markup Language

ČSN - Česká technická norma

FSC – Forest Stewardship Council

PEFC - Programme for the Endorsement of Forest Certification

BHD – Breast Height Diameter

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List of tables, graphs and pictures

1. Introduction

Ever since the mechanical and digital revolution in Forestry technology, the quality and volume of timber is easier to evaluate and predict the amount of financial profit gained in the harvesting. This has led countries such as Germany, Finland or Czech Republic to increase the use of harvesters as a main logging machine, with its main method of assortment processing method being cut-to-length. As of today, Finland uses CTL with 99 percent from all logging operations, where percentage rate of Czech Republic is roughly 37.7 percent (Zpráva o stavu lesa 2015), (Lindblad 2008). As CTL logging has seen as more environmental-friendly, safer for workers, and less time-consuming, it is also more expensive to execute in larger clear cuts and requires more educated personnel to maneuver. Nevertheless, it is the modern trend in global logging stage and more countries are increasing its use. (Richiewiki 2009)

To execute CTL -style logging properly, harvesters are required to house a set of modern hardware and software, which will enable them to measure, calculate and predict the assortments in every tree that is processed through it. These technologies include computer systems, GPS tracking, powerful but low-emission diesel engines, and various types of sensors scattered throughout the machine. However, arguably one of the most identifiable and crucial part of any harvester is its harvester head. It is responsible for timber felling and processing it to appropriate assortments, and assortment data production. This logging report data is often relied and referenced when economical profits of logging operations are calculated and paid to the forest owner. (Dooley & Nieuwenhuis 2006)

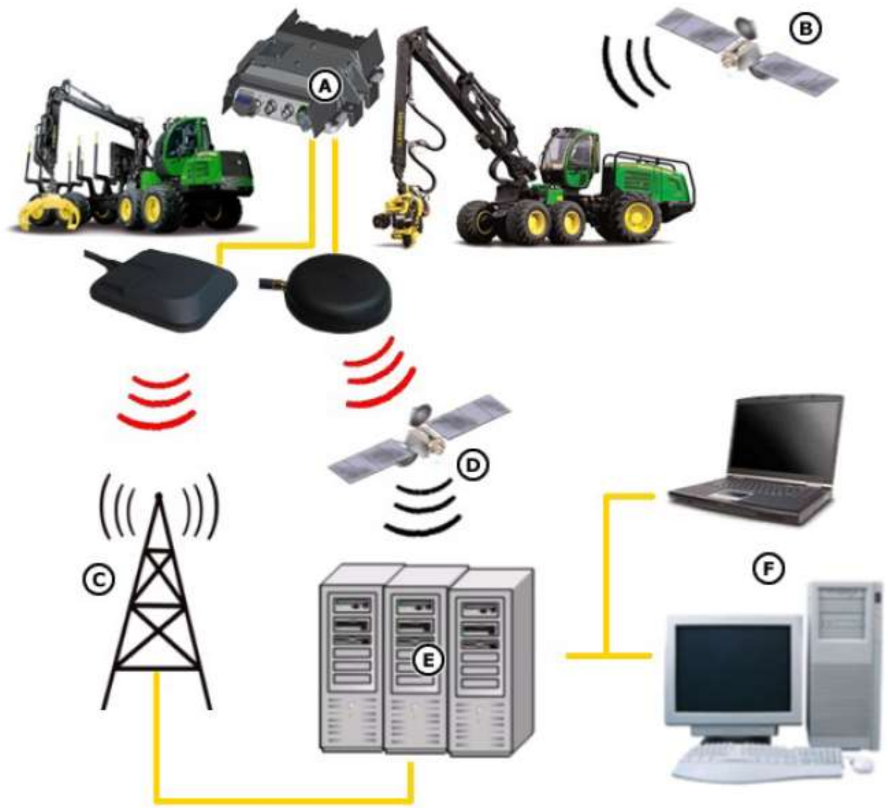
According to Richiewiki homepage on CTL –logging, it does not make the produced logging data absolutely accurate, as many factors of the machine, logging environment and operator condition affect the accuracy and reliability of the data, by producing skewed measurement data by under- or over measuring of the tree (Richiewiki 2009). Error produced in harvester head measurements from these factors can significantly minimize value recovery through poor selection of assortment combinations from each felled tree. Logs outside length and diameter specification may also need to be downgraded to lower value products, or docked, resulting in further economic losses. As uncertainty in always present in harvester measurement, it is crucial to acknowledge and study the factors connected to this measurement type. (Strandgard & Walsh 2012)

The target of this analysis is spread in to several parts. First objective is acquire measurement data from various field measurement methods and identify components and settings, which have the essential effect on the accuracy and reliability of timber measurement and scaling. Verification of the acquired knowledge will be done both in practice as field measurements and using the harvester simulator. Finally comparing the findings with the works of other authors. Reliability of different field measurement methods are also evaluated based on the exercise data. To keep the scale of field measurement analysis reasonable, the amount of felled trees was needed to keep relatively small and with single tree species, which was Norway spruce (*Picea Abies [L].Karst*). Adding the fact that the tree dimensions were measured various methods, larger tree sample amount would have proven to be excessively time-consuming. Also simulator research scale was narrowed down to specific tree size and one tree per parameter change.

2. Present state of the topic

2.1 Harvester technology utilization in forestry

After the first launch of fully mobile forest harvester PIKA model 75 in Finland in the year 1973, global forestry community has been utilizing harvesters in timber production, applying new technology in every decade to these versatile machines. The 1980’s brought single grip harvesters in to the logging, 90’s brought GPS (Global Positioning System), predictive bucking system, modern bucking module in the harvester head and overall basic structure of modern O.B.C.S (On Board Computer System) as a standard devices in harvesters. The 2000’s brought more complexity and variability in the computer systems with standardized Windows –interfaces, as well as new comfort and safety technology in the cabin, such as autotomized air-conditioning, high-speed mobile internet for data transfer and reinforced cabin windows. All these technology incorporations were aimed to improve working comfort and optimize operator productivity. (Haarlaa 1992)



Picture no:1 Illustration of the harvester data communication process. (John Deere 2014)

Harvesters are used effectively in level to mildly steep terrain in clear cuts and smaller size harvesters in thinning operations. For very steep slope terrains, loggers or skyline logging are preferred in some countries. Harvester can be used in salvage cuttings also, but it is considered not to be cost-effective in salvage cuttings low m^3-per-hour production rate. The main principle in mechanized logging is "*no feet on the forest floor*", meaning it aims to minimize the use of manual, manpowered logging. Harvester and forwarder allows this principle to be achieved, by keeping humans inside the cabin, as the machine provides more comfortable and safe working conditions for industrial scale logging. (Richiewiki 2009)

Harvesters are built on a sturdy all-terrain vehicle, either tracked or wheeled. The vehicle may be designed to provide tight turning capability around various forest obstacles. High-powered diesel engine provides power for both the vehicle and the harvesting mechanism through hydraulic drive. Retractable, articulated boom reaches out from the vehicle to carry the harvester head to target trees and pulling felled trees to procession area. Some harvesters are adaptations from excavators with new harvester head, but mainly they are purpose built vehicles, solely on logging. "Combi" machines are also considered to be harvesters, although these combine the felling capability of a harvester with the log-carrying capability of a forwarder, allowing a single operator and machine to fell, process and transport trees. However these are rarely used in industrialized logging, as these are competitive only in operations with short distances to the landing. (Richiewiki 2009), (Melkas & Visala 2009)

2.1 Timber measurement systems in Europe

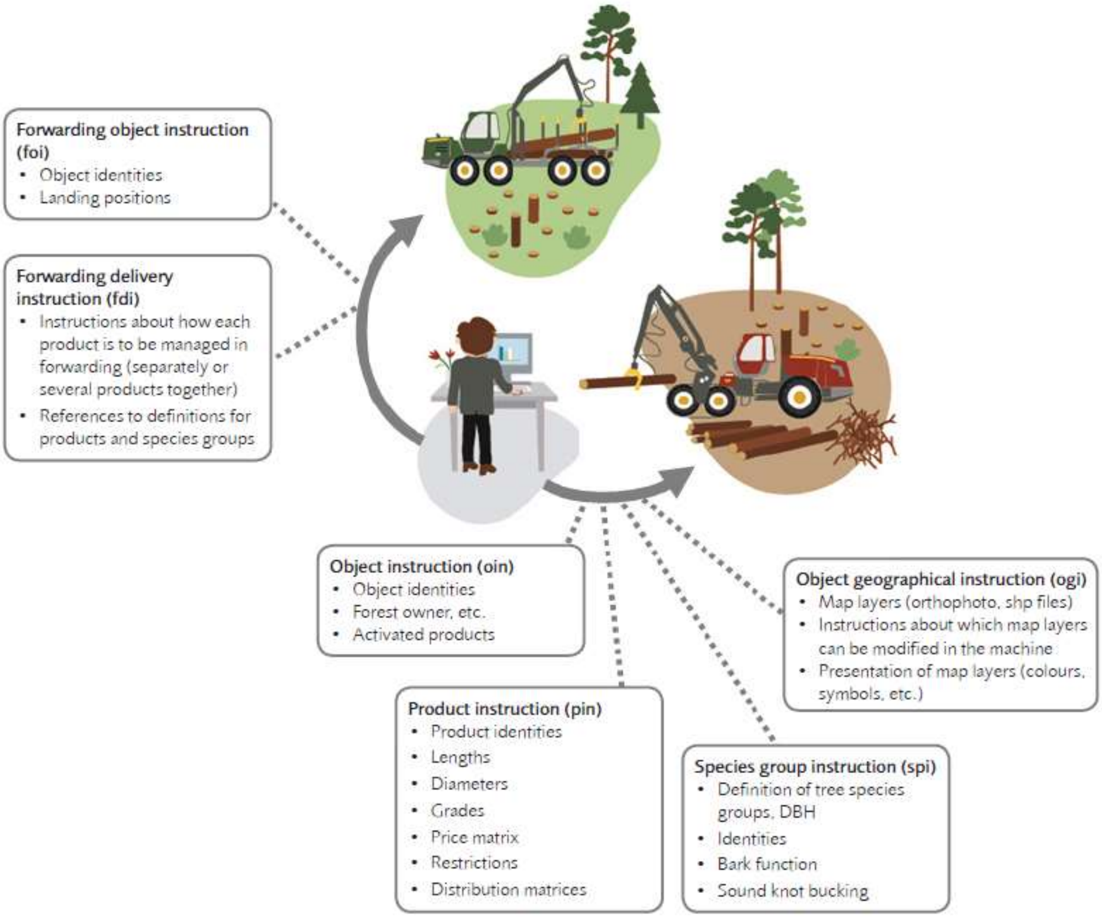
2.1.1 Standard for Forest machine Data and Communication – StanFordD 2010

According to the Skogforks internet homepage, StanFordD is the forestry sectors standard for management of data to and from all forest machines. It is a global standard in CTL style logging which most countries follow, although it has yet to be granted any official standard status. It has been coordinated by Skogsforks of Sweden from 1987 and was set in its standard form in the 90's, when large forest machine manufacturers agreed to finance the administrative work together with the Swedish forest companies through Skogforsk. The first model of StanForD mainly compromised data- and file structure standard and Kermit-based communications protocol or PC connecting and data recording in the harvesters. After 2006, new standard model of StanForD2010 was released, which is the one that is used today. (Skogforsk 2014), (StanForD 2010)

StanForD 2010 uses the XML (Extensible Markup Language) format for storing information, which is an open, general format that is used in many applications where data needs to be stored and communicated with. This can help avoid unnecessary conversion with other formats in communication with different data management systems. XML has the major advantage for software developers that there are already many complete and freely available solutions for reading and managing XML files, which saves time and development resources. In addition, files can easily be checked against the XML Schema to ensure that they comply with the standard. Even if XML files are large, they are easy to compress with zip compression, which saves space and requires less transfer capacity. The compressed XML files are generally no bigger than the earlier StanForD files. (Skogforsk 2014), (StanForD 2010). This system is involved at several functions in the harvester and forwarder systems:

- Production control & reporting
- Quality assurance
- Operational monitoring
- File transfer protocol between calliper (or other equipment) and O.B.C.S
- Version management

The file structure in StanForD 2010 is based on a number of messages for control, production reporting, quality assurance and operational monitoring. In order to distinguish between various types of messages, a system of filename extensions is used, as shown in the picture number 2. (Skogforsk 2014), (StanForD 2010)

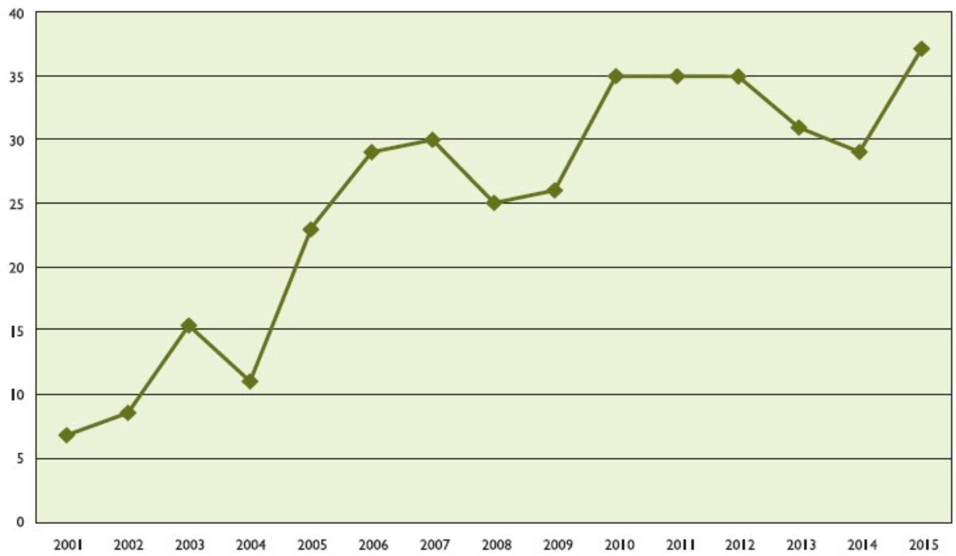


Picture no.2: Various controlling messages harvesters and forwarders in StanForD 2010 system (www.skogforsk.se)

According to European Committee of Standardization (CEN) publishment "*Round and sawn timber - Method of measurement of dimensions - Part 2: Round timber - Requirements for measurement and volume calculation rules*", Many different timber measurement rules exist in Europe. These rules and method have come in to being based on historical influences and traditions, and sawmilling and forestry data is based on these differing ways of timber measurement. As diverse set of methods and rules exist in different countries (and some cases different regions inside of a country), it is currently very problematic to lay down single set of acceptable rules for all member states. This standard publishment was therefore created to give basic principles, when drawing up round timber measurement rules and methods. It is composed of two annexes, first being informative and second normative (which applies to nations that doesn't have existing rules for measurement standards). (CEN 2005)

2.1.2 Czech Republic

According to Dvořák et al, the end of seventies marked the first arrival of harvester technology in Czech Republic, with machines such as Volvo BM and ÖSA. These machines utilized tree-length harvesting technology and the timber transportation method was mainly skidding. It would take another decade for the single grip harvester to reach general populace of professional forestry companies, however these harvesters still utilized manual measurement with tape and calliper. The beginning of nineties brought significant harvester technology improvement, and with it the cut-to-length (CTL) technology in logging. At present state, approximately 30-35 percent of this technology is applied in all forest harvesting (531 operating harvesters and 1017 forwarders). (Dvořák et al. 2011), (Zpráva o stavu lesa 2015)



Picture no.3: CTL –technology development in Czech Republic. (ZPRÁVA O STAVU LESA, 2015)

Several types of measurement systems exist in Czech Republic today, all which meet the standards set by EU and CEN European standards of round wood and sawn timber (unofficial translations in italics):

- ČSN 48 0007 Tabulky objemu kulatiny podle středové tloušťky *Tables of logs volume according to mid diameter*
- ČSN 48 0008 Tabulky objemu výřezů podle čepové tloušťky *Tables of logs volume according to top diameter*

- ČSN 48 0009 Tabulky objemu kulatiny bez kůry podle středové tloušťky měřené v kůře *Volume tables of roundwood under bark according to mid diameter measured over bark*
- ČSN 48 0050 Surové dříví – Základní a společná ustanovení *Rough wood – Basic and common regulations*
- ČSN 48 0055 Jehličnaté sortimenty surového dříví – Technické požadavky *Coniferous assortments of raw wood – Technical requirements*
- ČSN 48 0056 Listnaté sortimenrty surového dříví – Technické požadavky *Broadleaved assortments of raw wood – Technical requirements* (CEN 2005)

According to Sladek and Neruda, As the terrain or forest stand characteristics or economical demand of logging operation may limit harvester and CTL technology deployment in CR forests, many logging operations still utilize manual logging and measurement by tape and calliper, or the measurement data is provided by the sawmill after the timber is transported to the sawmill, or yard. (Sladek & Neruda 2007), (Zpráva O Stavu 2015)

After EU set standard rules in in timber measurement, CR developed their own guidelines in the paper *"Recommended rules to measure and classify wood in the CR"* (2002), which describe the allowed methods for timber measurement and volume calculation. However, presently there does not exist minimum requirements for technical parameters of electronic measurement systems, the method of data processing or accurate specification and required accuracy of the system calibration. Most likely this fact has led to different value determination in suppliers and customers, which has led to timber measurement accuracy being under questioning. Although non-state organizations such as FSC or PEFC has demands and guidelines of sustainable wood production and procurement, it has yet to determine anything accuracy and calibration related quidelines. (Sladek & Neruda 2007)

2.1.3 Finland

Erkki Kare of TEKES -institution described the birth of mechanization era in Finnish logging operations. He wrote that the first double grip harvesters appeared in the field during of 1960's, that could process timber in CTL method (during this time tree-length method was mainly used in logging operations). Such machines were Pika 50 and Log All feller buncher/skidder –hybrid, the latter which utilized full-tree method. The end of 60's saw the arrival of first single-grip harvester, Pika 75. This model used CTL method for logging and was one of the first ones to have a simple computerized bucking system to optimize cutting windows for each assortment. (Kare 2015)

During 80's and 90's harvester technology developed more sophisticated O.B.C.S, which included GPS and printable documents of logging operation progresses in the system. Also the pulse sensor technology was implanted as a vital part of tree measurement in single-grip harvesters. One of the pioneers of such diverse set of integrated technologies was Ponsse Oyj, which started as a small-scale forest tractor manufacturer, but surpassed the competition after 90's of such business rivals as Lokomo and Valmet. Nowadays it is the one of most prestigious companies of forest technology development. (Kare 2015)

Picture no.4: Newest innovation from Ponsse: Scorpion harvester. (www.ponsse.com)

According to Lindblad's article in *"Tapion Taskukirja"* At present state Finnish logging operations are 98 percently done by harvester-forwarder combination with CTL method. Only extreme terrain conditions (such as wet peat lands or steep slopes) or low profitability sites are harvested manually by loggers, and extracted by forwarders.

Cableyards or use of skidders have been considered unnecessary or slow to utilize in Finnish conditions. (Lindblad 2008)

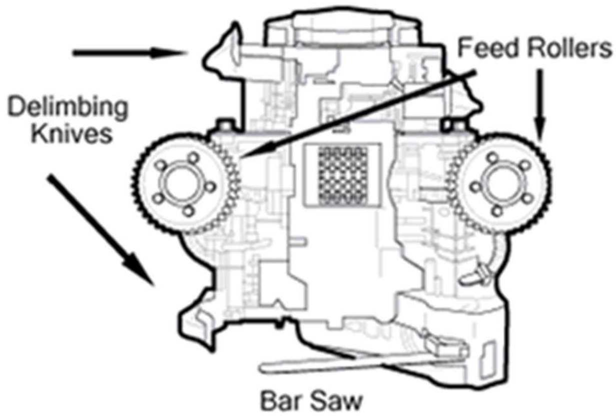
Different types of wood procurement and transport chains set their own demands of measurement in Finnish timber production. In addition, possibilities of timber measurement vary, depending on different logging phases and specific assortment types. According to Finland Ministry of Agriculture and Forestry, over ten different legally verified timber measurement methods exist today. Based on the annual harvested timber volumes, measurement data produced by harvester or sawmill are the most important among all the methods. One of most typical measurement systems in Finland are combined sawmill and harvester measurement –system, where timber is first measured in the forest by the harvester and then in the sawmill. As the sawmill measurement technology is considered to be more reliable and accurate, this method is the point in which the harvester data is being referenced to, thus producing error percentage (which can fluctuate ±4 percent by the Finnish standards). (Lindblad 2008)

Rest of the measurement methods have very little use with commercial wood procurement. Measurement of standing trees has been decreased with mechanized logging and the logging data reports. In addition, stacked wood measurements have been consciously reduced in the commercial field, because it has been considered expensive and time-consuming, when compared to harvester- or sawmill measurement. However, stacked wood measurement methods are still in use in small scale logging operations and timber purchases in cash. The method of measurement is often decided when timber procurement contract is signed. (Lindblad 2008)

2.2 Mechanical-electronic measurement and scaling devises in major harvester manufacturers

2.2.1 Basic system characteristics for all harvester types and models

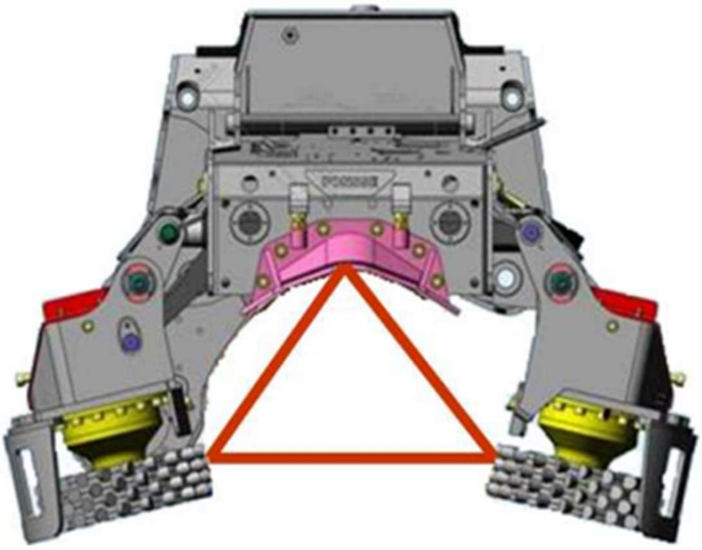
Timber measurement in harvesters can be divided in to several sections for data accumulation and calculation. According to the study of "*Measuring Log Length using Computer Stereo Vision in Harvester Head*" from Kalmari et al in 2011, harvester head gathers the data with the sensors attached to the delimbing knives, gripping wheels or separate length sensor wheel, and sends the unprocessed data to the module in the harvester head, which further sends the data to the module in the cabin. The cabin module, along with the designated software calculates the volume and presents individual results of the processed assortments. (Ovaskainen 2009), (Kalmari et al. 2011)



*Picture no.5: Basic components of harvester head. (*forestsandrangelands)

The length measurement is done by either specific pulse method with specialized wheel in the heart of the harvester head or the feed rollers. These pulses are generated by the sensor in the wheel as it spins in the tree surface, then sent to the On-Board-Computer-System (O.B.C.S) in the cabin module, as delimbing takes place. The O.B.C.S uses a pre-determined factor, stored within its memory. The computer converts this pulse count into actual length measurement before displaying it on the in computer screen as log length. (Innovawood 2006) In the article "*Assessing the role of the harvester in forestry-wood chain*" at forest Products Journal volume 51, Chiorescu Sorin wrote that the harvesters length-measuring device has a certain measurement accuracy along with diameter measurement accuracy has an influence on the precision of the bucking operation and so downstream the final length of the sawn timber. (Chiorescu & Grönlund 2000)

In the paper "*Round Wood Measurement System*", Karel Janák wrote that the diameter is also measured by the pulse technique, but the data is gathered by the deviation of delimbing knives or feed rollers. The method for diameter measurement is called triangulation measurement, which measures the positions of the knives or feed rollers, then compares it to the point of the harvester head surface. This data is captured usually by pulse sensors or by potentiometer. Series of pulses are created every 1 to 10 centimeters, which are fed to the O.B.C.S. The computer converts this pulse count into actual diameter measurement, which is displayed in the computer. It is also stated that scanning straight by the feed rollers is not used often today, due to its likeliness of slippage of cylinders in the stem surface. (Janák 2012), (Innovawood 2006)



Picture no.6: Triangulation method. (Lappi 2014)

In his Bachelor Thesis of 2014, Jussi Lappi wrote about harvester measurement systems, and Ponsse Opti6 system in particular. In that thesis he states that the data collection in major harvester manufacturers is essentially the same. Harvester head collects the raw data to the harvester head module, which is sent to cabin module for procession and projection in the computer system. This applies to the primary information system as well, as most of them are managed by Windows –based operating system. However the differences lie in the overall control systems in bucking, logging management and machine operating system. Every harvester manufacturer have designed their own systems that are optimized for logging in that specific machine. (Lappi 2014)

2.2.2 Ponsse

According to Ponsse, "*Opti4G is the operator's user interface with the machine control system. In addition, it handles all of the operations required for cutting from data transfer to marking for bucking and reporting*". It controls all sectors for bucking, calibration, data transfer and management. The system also produces other harvesting information, such as tracking operator working hours, output, machine operation and fuel consumption. Opti4G

System programs offers convenience while driving, tagging files for evaluation and calibration of equipment. Opti4G is fully compatible with all standard control systems harvester. The system is based on the current Windows operating system and personal computer which facilitates data transfer and map applications to the harvester. (Ponsse 2015)

The needs of sawmill or forest owner determine how logs are cut in the felling site. Opti4G automation system makes the operator's work easier by controlling the bucking according to the requirements stored in the system. In their commercial brochure, Ponsse states that "*OptiControl makes machine control easier, with the crane, handles and buttons, drive transmission and diesel engine operating as a single easy-to-use entity*". Once the operator logs in the system, the program begins to collect information of work time, production, machine operations and fuel consumption. These reports can view all this information on a single screen. (Ponsse 2015)

Picture no.7: Ponsse harvester cabin with running Opti4G. (Ponsse 2015)

2.2.3 John Deere

John Deere harvester systems can be divided in two separate systems according to its homepage, the Timbermatic H-12 and H-16. The first is designed for harvesters in E-series and the latter for G-series. The real differences between these two operating systems are rather small, being in the outlook of the systems interface and settings. (John Deere 2016), (Suuriniemi 2015)

Timbermatic H operating system consists of machine control, bucking and calibration. As other systems, all the needed information is displayed in one screen. One major advantage is the user-friendly settings system, which allows the user to adjust: (John Deere 2016)

- Machine operations in one button press
- Driver-specific settings in boom, machine and bucking control
- Interactive menus
- Electric guidebook build for easy access

In the article "*John Deere's G-Series harvesters and forwarders – More than a machine*" John Deere employee Elina Suuriniemi describes the operating system. The adjustable system also allows the user to manipulate more complex functions to suit the needs in specific situations. These functions lets the user adjust the hydraulic pressure in boom controls, harvester head controls, but also pressure for delimb knives and drive pump and gearbox pump. This helps to adapt any felling sites demands. However, these adjustments require experience in hydraulics and are not recommended for new users. (Suuriniemi 2015)

2.2.4 Komatsu

The commercial brochure "*Control and Information Systems*" of Komatsu Forest, the basic harvester information system, the Maxi -system is described. It consists of three softwares, each one suited to different machine type: MaxiXplorer, forwarding MaxiForwarder and other machines equipped with Komatsu Harvester heads MaxiHead. The MaxiXplorer is the primary system in all Komatsu harvesters, which controls all the functions for machine and head control, crosscutting, and administration. One important profitability factor is the exceptional user friendliness. The modern graphic user interface and simple menu structures make MaxiXplorer easy to use. The user can create reports for any time period as needed. This provides flexible and “all-in-one” follow-ups rather than separate files. The user interface structure and outlook is very simplified. (Komatsu 2015)

In the Master Thesis “Head-Mounted Displays for Harvester Operators – A Pilot Study”, Anders Nordlie and Staffal Till further describe the MaxiXplorer system. It is stated that another feature in this system is the configuration possibilities in all the joystick buttons, meaning that the user can assign any function on anywhere in the joystick. This feature is unique to the Komatsu harvesters and MaxiXplorer –system. However the buttons does not contain any symbols or markings, making new-time users spend more time learning on the buttons. The system offers standard possibilities in the field of user modification. Crane controls, movement acceleration, hydraulic pressures and bucking are few of the notable things that can be adjusted and saved for every user. (Nordlie, Staffan 2015), (Komatsu 2015)

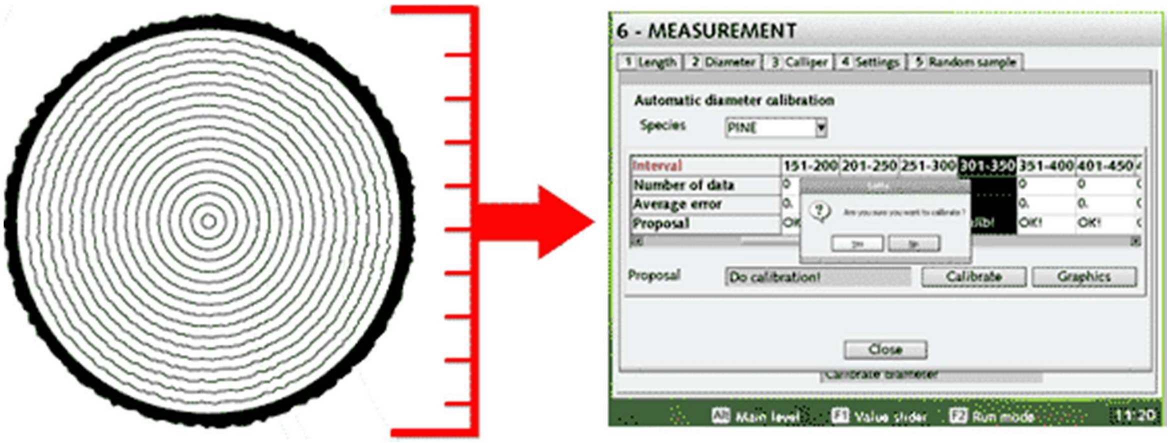
2.2.5 Rottne

According to Rottne official homepage and commercial brochure, Rottne Forester is the new generation of bucking system which fulfills the requirements of StanForD 2010 -standard. The cab features a large, clear 15″ touch screen and a keyboard in front of the operator, as well as a printer that is integrated into the ceiling panel. The screen displays length and diameter as well as other information on the tree currently being processed by the harvester head. Easy generation of production reports. It coexists with Rottne D5, a control system that is based on CAN bus technology and controls and monitors the engine, transmission and loader. (Rottne 2016), (Rottne 2015)

This system consists of different computerized modules, which are interconnected through EtherCat technology. It is equipped with 15" touch screen (used for both D5 and Forester) and keyboard installed in the cab as well as a printer mounted in the roof panel. The screen displays length, diameter as well as other information on the tree currently being processed by the harvester head. The touch screen also enables settings to be made and modified as well as generation of production reports. Data entry and price list changes are done using the keyboard. Communication takes place via USB memory, e-mail or printer. Bucking is optimized with value bucking, but as an option there is also a more basic program for priority bucking (Rottne 2016), (Rottne 2015)

2.3 Harvester calibration

As the demand and supply remain stable, mechanization and digitation will provide the edge needed to increase reliability of mechanized harvester and finally, productivity of the entire supply chain. One of the aspects of this edge is accuracy of harvester bucking system. Many countries and global companies rely on the harvester logging data to be the most relevant and reliable. (Lappi, 2014)



Picture no.8: Production of harvester head calibration measurement (Innovawood 2006)

In the abstract of the journal "*Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas fir*", Acuna and Murphy further discuss the mechanization of modern logging, which are now days outfitted with rudimentary sensor systems which measure the external dimensions. These sensors play the central role in the overall accuracy of entire logging operations, and should be maintained in regular intervals to decrease the error percent in the bucking system. (Acuna 2007)

Innovawood portal homepage describes the calibration method basics. It starts by the predetermination of the calibration scale, meaning how many target logs will be processed by the harvester and what is the diameter measurement interval for these logs. These parameters are set by the expectancy of the error percent. For example, if the harvester heads sensors are suspected to have high probability for producing negative error in length measurement, the diameter measurement interval is set to 50 centimeters and the amount of logs around 50. Basically this lowers the confidence interval of the measurement data. (Innovawood, 2006) (Nieuwenhuis & Tadhg 2006)

Ponsse educational calibration brochure, “Ponsse Opti 4G Satunnaisotantamittaus” describes the digitized harvester calibration method in two ways, the typical calibration and random sampling calibration. In the typical calibration section, it is written how the calibration event proceeds after presetting calibration scale. After the calibration scale determination, the harvester starts the target tree felling, processing the wood in assortments with typical cut-to-length fashion. After the target number of trees has been reached, the operator ends the calibration felling by storing the data for each tree that has felled in the system, and if used by digital caliper, in the calipers system as well. The trees are then measured by digital or traditional non-digital caliper in the exact order as they were felled and processed by the harvester. (Ponsse satunnaisotantamittaus 2016), (Masser 2016)

Picture no.9: Typical calibration event in a snowy environment.

Diameter measurement interval is predetermined in the pre-setup of the calibration and must follow that set value, which is typically around 30-100 centimeters. Each of these interval sections are cross-measured, meaning that the diameter is measured twice in opposing parts of the stem. This gives more accurate diameter data results, especially if the tree stem is irregular in form. Length of each assortment is also measured manually by the accuracy of tens of millimeters. After this the next step depends on the technology that is used in the calibration, the digitized caliper or the traditional. It also should be noted that every official harvester head sensor calibration is done according to the StanforD-standards, which describes the parameters and overall methodology. (Ponsse satunnaisotantamittaus 2016, (Sladek & Neruda 2007)

Automatic calibration can be divided in to full sampling and random sampling calibration, depending on the harvester system. Automatic calibration with full sampling method refers mainly to the usage of digitized caliper along with the on-board-computer-system (O.B.C.S) of the harvester. In their commercial brochure "*Timbermatic Measuring and Control Systems*" describe the automatic method of calibration. Despite the fact that it describes the John Deere harvester calibration, it is stated that the method is very similar in every other harvester systems. After the pre-setting the calibration scale in the O.B.C.S, and processing of the target trees, the settings for the calibration with the measurement data is uploaded in to the digitized calliper and set the calibration event in the calliper system to run. Calliper then automatically suggests the number of the felled tree and the processed log in numerical order (from first tree and first log to second log, etc.), which the operator follows to avoid any measurement error caused by measuring the wrong assortment in the wrong order. (John Deere 2012), (Bembenek, 2015)

Picture no.10: Digital calliper produced by Masser Sonar. (Massser 2016)

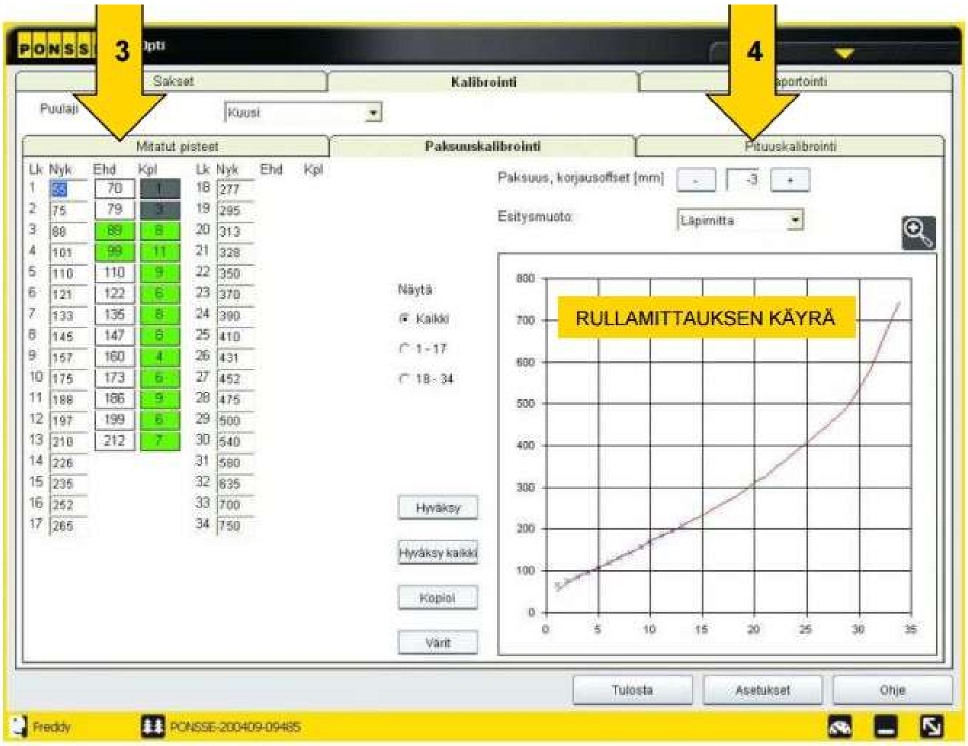
Every measurement point of the assortments are cross-measured and each diameter data is stored in the calliper, as well as the full length of the assortment. As all the target assortments are measured, the operator ends the calibration event in the calliper and plugs it in the O.B.C.S, uploading the caliper measurement data in the system. The data is then processed and displayed in the computer screen. The computer also compares the caliper data to the harvester head data, bringing any irregularities in each measurement sensor unit in the harvester head. Operator can report this calibration event and the measurement data on both sources, the caliper and harvester head, in case forestry officials need it. Finishing the event, the operator can change the sensor values and parameters that the computer system suggest, in order to decrease the error percent in individual measurement sensor and finally, the overall error percent in the whole system. (Kalmari et al. 2011), (Bembenek et al. 2014)

Random sampling starts with the presetting the parameters, which define the event when computer selects a tree as calibration measurement during normal felling. These parameters are drawing scale where the calibration event will randomly occur, minimum & maximum diameter of sample tree, target tree species, and time frame of the calibration event. After the parameters are set, operator continues the logging operation normally, until the O.B.C.S randomly alerts the operator of a tree that has been selected to as a sample tree for calibration. Tree is then processed normally in to assortments and data sent to the digitized calliper. It should also be noted that this calibration method is not viable for complete harvester head sensor calibration, as the one tree data is concidered insufficient. (Ponsse satunnaisotantamittaus 2016), (Korpilahti et al. 2006)

In the research "*The Effect of Calibration on the Accuracy of Harvester Measurements*", Nieuwenhuis and Dooley conducted calibration with manual calipers and also described the standard methodology to study the effectiveness of calibration. Manual calibration starts with the same calibration scale preset as it does in automated full sampling methods. The harvesting of the target trees is also the same, but the caliper measurement and data input is different. After the target sample trees have been felled and processed, they are measured by tape-and-caliper in the measurement points that have been set by the O.B.C.S. The diameter and length data is stored either in laptop computer, or written in paper. After the measurement is finished, measurement data is either uploaded from the laptop to the O.B.C.S or manually input from the paper in to the system's calibration charts. (Dooley & Nieuwenhuis 2006)

Ponsse describes the diameter and length calibration of the Opti 4G system with high detail in their educational brochure. Although it is concentrated only their systems, sources from John Deere Forestry and Komatsu Forest suggest that the methods are the same, only system interface differ. (Ponsse satunnaisotantamittaus 2016), (John Deere 2012), (Komatsu 2015)

The length parameter is modified using a regression curve, which is based on the feeding rollers or measurement wheel data. Its vertical-axle presents the length curve classes and horizontal is overall length. There also exists a calibration table which shows the suggested lengths and measured lengths. This table also has color symbols to present the calibration status for each length class. Green stands for credible values, red means that imminent correction is required and white/yellow is a correction suggestion. Operator can modify either the table or the regression curve for length correction, but normally the table is used. The parameters are all displayed in length classes. (Ponsse 2016) (John Deere 2012) (Komatsu 2015)



Picture no.11 Diameter calibration screen in Finnish Ponsse Opti 4G. (Ponsse 2016)

Diameter parameters can be modified if the sample size of the control calibration is large enough. The calibration screen in the O.B.C.S is highly similar to the length calibration screen, with adjustable table and regression curve with diameter classes and overall diameters. The operator follows color themed suggestions produced by the system and makes corrections accordingly. If the calibration produces clearly positive or negative diameter measurement errors in all assortments, it can be generally corrected with Offset correction, which corrects the sensors in millimeters. For example, if both log and pulpwood both produce positive diameter measurement error, it should be adjusted in the Offset. However the diameter calibration is more complex, if several assortments require both negative and positive correction. These corrections need to be adjusted in the regression curve individually. (Ponsse 2016), (John Deere 2012), (Komatsu 2015)

2.4 Timber length and diameter measurement error

Timber measurement is based on mechanical- and electronic sensor technology, which will wear out in time and in intensive utilization. As the sensors wear out or some external factor applies in the measurement event, the measurement data output from the system begins to differ from the real lengths, diameters and volumes of the trees. After the sensor calibration event, the system can compare its own measurement data to the manually measured data, calculating the differences between and producing modification suggestions, presented as the measurement error. This measurement error is essential method used by the O.B.C.S to describe how this error is affecting the logging data accuracy. It is presented by negative or positive percentage number in the system, in both diameter and length sections and for every tree species individually. (Sirohi & Radha Krishna 1991), (Dooley et al. 2006)

In the research "*Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands*" Hamish et al. described the features of measurement error in forestry, as well as its economic impacts. They stated that every measurement, including harvester measurement contains some level of error, systematic or random. Causes of systematic error in harvesters are considered to be in the system settings, measurement sensor malfunctions and lack of operator's professional skill, where random errors are mostly caused by weather, logging site conditions and season. Systematic errors especially in length are a fixed amount, regardless of log length. However, systematic errors in diameter can vary across the diameter range (meaning each diameter point may have a different systematic error). It is also written that operator mistakes or gross blunders should not be considered as part of measurement error. (Hamish et al. 2011), (Strandgard & Walsh 2012)

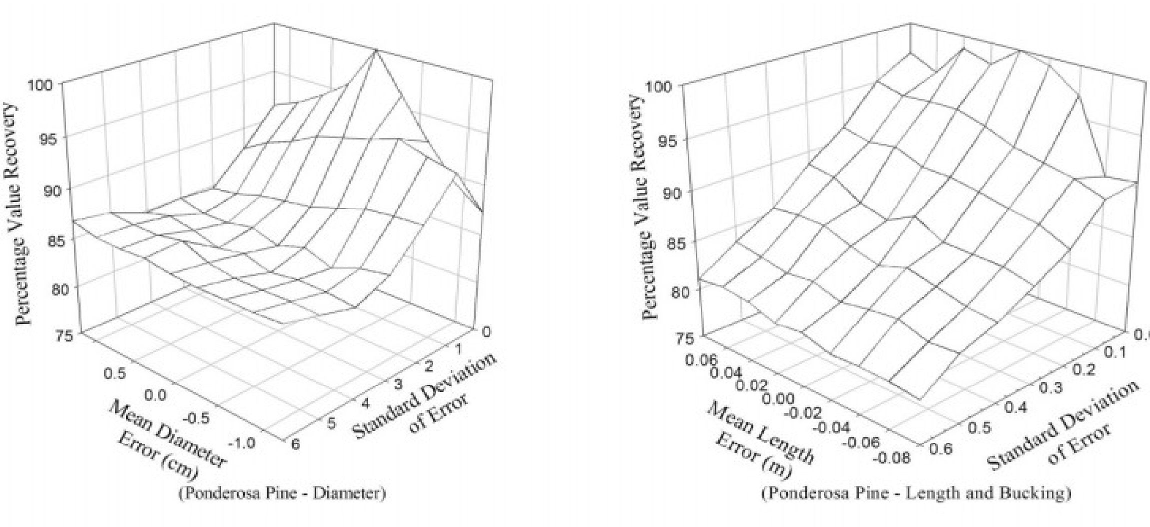
System and sensor calibration can decrease both random and systematic measurement error, but some random measurement error occur in such irregular intervals (irregularly shaped and thickly branched tree stems for example), that calibration or system parameter modification does not affect it. (Hamish et al. 2011), (Dooley et al. 2006)

Comparative analysis can be subjected to number of errors which affect the accuracy and reliability of the results. Therefore it is important to acknowledge and identify these error types, and the events in which they might occur. Commonly, in measurements exist three main types of errors: gross, systematic and random.

Gross errors are considered as human errors and they can be avoided by taking proper care during data recording and measurement, and by increasing the number of experimenters. If each experimenter takes different reading at different points, then by taking average of more readings we can reduce the gross errors. Systematical errors can be categorized as environmental and instrumental error types. Instrumental errors may occur due to friction, hysteresis, loading effect or misuse of the instruments. To minimize the gross errors in measurement various correction factors should be applied and in extreme condition instrument must be re-calibrated and maintained regularly. Environmental errors may arise due to conditions external to the measurement instrument. These external conditions include temperature, pressure, humidity or it may include external magnetic field. This error can be minimized by manipulating the measurement environment to ideal state (humidity adjustment for example), or in forestry choosing specific time period or season which would be ideal for data recording. Random error or stochastic error are more difficult to identify and prevent. Stochastic errors tend to be normally distributed when the stochastic error is the sum of many independent random errors because of the central limit theorem. Hence we cannot fully eliminate these kinds of error. (Electrical4u, 2011)

2.5 Significance of measurement error in forestry

It was considered in the past that impacts of high error measurement percentage affects length and diameter measuring accuracy of harvesters, which will have an influence on the precision and quality of the logging operations, which in succession decreases the credibility of the logging enterprise. However, it has been estimated that in Norway spruce that measurement error could cause approximately 1 percent loss in economic value, according to research results by Sondell et al in 2002. Supporting this claim, the research of Hamish et al. in 2011 suggested that high measurement error percentage has significant negative economic impacts as well, as it reduces value recovery through poor selection of product combinations from each stem. Logs outside size specification may also need to be downgraded to lower value products, or docked, resulting in further losses. In this research a simulation model was established to estimate the value loss caused by these errors. The results of the simulation model proved that the logging operations were losing potential timber value between 3 and 23 percent depending on the type of measurement error, the level of error and the species. In the five studies of this research where the diameters were on average being underestimated, the diameter error losses were much larger than those due to length measurement error during stem measurement. This discovery applies to both negative and positive error measurement, because most of forestry enterprises have both measurement error types regulated in certified logging operations. (Sondell et al. 2002), (Hamish et al. 2011)



Picture no.12: The effects of different levels of accuracy and precision of length and diameter measurements on percent value of recovery. (Hamish et al. 2011)

Theoretical maximum value recovery (i.e producing timber with 0 percent error measurement from the harvester) can be extremely rare to achieve, due to the market constraints, losses from mechanical damage and measurement errors. Diameter measurement error has been considered to have greater impact on value recovery than length measurement error. Under-measurement of length and diameter has a greater impact on value recovery than over-measurement, as under-diameter logs can fall into a lower price category and under-length logs may need to be docked to the next acceptable size. The greater value loss for under-measurement of log dimensions can result in harvesters being adjusted to cut logs slightly over length and diameter specifications, to minimise the number of rejected logs. The impact of harvester log length and diameter measurement inaccuracies on value recovery is dependent on the magnitude of the length and diameter measurement errors. Ultimately these have direct impact on economical profit on logging. (Murphy 2003), (Strandgard & Walsh 2012)

There exists no universal standards for harvester measurement accuracy, although two Swedish standards (at least 90 percent of saw logs in the "Best-5" adjacent 1 cm length classes and at least 90 percent of saw log small end diameters (SEDs) within ±4 mm of manual measurements) have been used in few researches. Despite this, depending on the individual measurement processing systems in individual Countries, the error percentage allowance is anywhere between 2 – 10 percent. For example, Finnish Forestry sector stipulates that harvester volume estimates (acronym for measurement error percent) must be ± 4 percent of the true stand volume at all operating times. The logging enterprise and lumber procurement companies are liable to keep this volume estimate in check by frequent calibrations and sensor maintenance. If the company produces timber with error percentage over 4 percent, it results a reminder to calibrate and maintain the harvester measurement systems, but frequent violations of this ordinance can results in the removal of the logging company from the lumber procurement chain. (Strandgard & Walsh 2012)

Violation of this ordinance also decreases the overall credibility of said logging company, and in worst terms might prevent from acquiring new logging contracts from other lumber procurement companies. On a smaller scale, it also affects the credibility and reputation of the operator, resulting of imminent denouncement from the company. Further employment possibilities are thus significantly reduced, when the reputation of this operator is decreased among other logging employers. (Strandgard & Walsh 2012)

2.6 Factors affecting the measurement reliability of timber scaling and measurement in harvesters

2.6.1 Factors affected by nature and site conditions

Prevailing season for wood production causes many changes to the tree structure as well as volume. These factors have immediate effect on the harvester measurement accuracy. (Miettinen), (Nieuwenhus)

Mikko Pulkkinen in his Bachelor thesis "*The affect of the temperature when mechanically measuring the length of a tree trunk*" further studied the phenomena with length measurement. He wrote that just -10 Celsius degree change in the tree causes changes in the length and diameter measurement, due to the stem surface freeze and the measuring wheel does not sink in as effectively as it would in normal summer season. Winter-, autumn-, and springtime -10 degree change has seen affecting the length measurement in 52 decimeter log for over 6 centimeters. This might cause the log to get rejected in the receiving area of a saw or plywood mill, because the length measurement result for every log to vary greatly between sawmill measurement and harvester head measurement. (Pulkkinen, 2009)

Frozen tree can also cause slipping in the tree stem, as the measurement wheel or feed rollers are not sinked in to the stem deep enough. This causes problems especially with trees that have thick branches. The harvester head does not apply decent grip in frozen tree, therefore delimbing can stop entirely and cause slipping if it gets stuck in thick branch, thus producing too high length measurement data. (Miettinen) (Pulkkinen, 2009)

Picture no.13: Experiment on the frozen stem with measurement wheel piece. (Pulkkinen, 2009)

Seasons bring also a significant changes to the diameter measurement accuracy. It has been considered that summer and autumn are best seasons to gain most accurate results. This is due to the fact that during these seasons the tree is fresh and the feed rollers sink in to the stem properly, while wintertime produces its own problems with diameter measurement that are linked to the problem explained above. However, at springtime the tree experiences rapid changes in weather (over 15 degrees difference between day and night) and in diameter growth. When new cells at phloem are generated and the tree bark is sensitive to mechanical damage and pressure. This directly affect the delimbing knives placement in the stem during the cutting event, as they apply around 200 Bars of pressure in to the stem. Pressure can easily break the fragile bark during springtime and cause variable results in diameter measurement, if the processed log is half debarked and half has bark intact. Also the time of year during which harvesting takes place and its effect on the cohesion between bark and the underlying wood is another factor that may have an impact on length measurement accuracy in particular. If bark gets detached from the wood, the harvesting head wheel that is used for length measurement will measure the length of bark going through the harvesting head, not the length of the log (Kekkonen, 2009), (Pulkkinen, 2009)

Conditions of the site are a great factor in harvester measurement accuracy. Tree density, structure and overall quality raises the risk of measurement error produced in logging, if full attention is not given to said conditions. (Visala, 2009)

Heikki Ovaskainen explored the issues of unmanaged stands in his Academic dissertation named "*Timber harvester operators working technique in first thinning and the importance of cognitive abilities on work productivity*". He explained that if the site has dense under canopy layer from younger tree generations, it is considered to affect harvester head measurement accuracy in all aspects. When the harvester head moves to the desired tree for felling, seedling trees get unintentionally caught in the grip between the delimbing knives and harvester head body. This affects the pre-felling diameter measurement by measuring the diameter larger what the tree actually is. As the head starts to process the tree, the bucking system predicts wrong assortments because of this error measurement, and processed logs will have incorrect diameter dimensions. (Ovaskainen, 2009)

This seedling problem might also affect the length measurement. When measurement wheel rolls through the stem surface, seedlings get stuck between the wheel and stem, stopping the measurement wheel while feed rollers still process log through the harvester head. This causes error in the system because system cannot use its predicting ability to reach the cutting point of single logs. (Ovaskainen, 2009), (Visala, 2009)

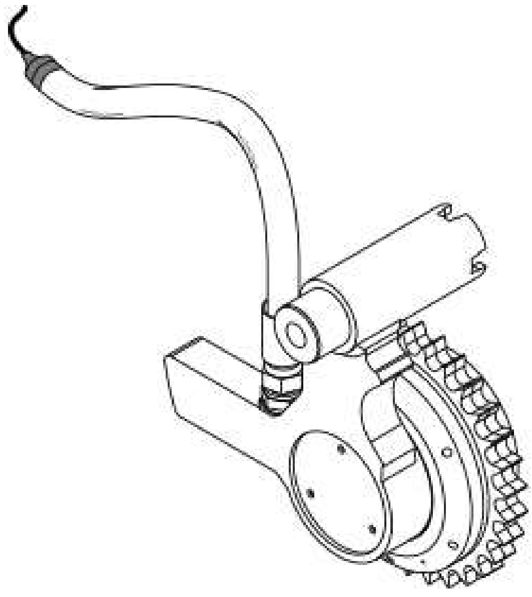
If such dense seedling exists through the logging site, the measurement accuracy error rises and ultimately might cause economical losses for the forest owner or entrepreneur who does the logging. It is known also to affect the operators working productivity. Therefore it is crucial to clear the under canopy trees before executing a harvest in the site. (Ovaskainen, 2009), (A. Kabeš)

2.6.2 Factors affected by harvester mechanics

2.6.2.1 Measuring wheel

Measuring wheel is an essential part of the length measurement system in harvesters, and therefore important to keep in good condition. Because the wheel is fitted with sensors and is on constant strain from logging, the sensor wears out approximately after 2000 working hours at optimal logging conditions. After that time the measurement wheel's components begun to malfunction, producing flawed length data. Pulkkinen (2009) describes several reasons what happens when the wheel starts to produce erroneous results. The usual reason is the wearing of the wheel bearing after long period of logging. When the bearing is old, the wheel does not roll normally at the surface of the stem and bearing might get stuck occasionally, producing short logging length. Other reasons include wearing of the sensor and data cord. These can cause the sensor to go offline momentarily, meaning that while the wheel rolls on the stem, the impulse generator does not capture any length data, or the cord does not transfer that data to the O.B.C.S. (Pulkkinen 2009), (Kalmari et al. 2011), (Innovawood 2006)

Reduced length measurement accuracy has been linked to heavy branching of the trees and loose or detach the measurement wheel from the bark. The increased errors result from the harvester losing its position on the stem during repeated delimbing passes or losing stem contact. All these flaws can be only repaired by replacing the old part with the new one, but old sensor data output error can be temporarily fixed by increasing the length calibration times when logging intensively. (Strandgard & Walsh 2012), (Pulkkinen 2009)



Picture no.14: Standard Measuring wheel (www.logmax.com)

2.6.2.2 Delimbing knives

In the Bachelor thesis "*Testing of the Ponsse Opti6 Measuring System. Testing methods and design of the test case for a field service technician*", Jussi Lappi briefly describes the problematic of diameter measurement with delimbing knives. He wrote that triangulation method has problems when measuring the diameter of irregularly shaped trees, because this method measures only three points, which in turn are not sufficient to produce viable measurement results of the real diameter dimensions of the tree. This problem only applies with irregular trees, but normal cylindrical shaped trees can be processed with the accuracy of 1 millimeter, which is insignificant in harvester measurement results. (Lappi 2014), (Janák 2012), (Sirohi & Radha Krishna 1991)

Picture no.15: Standard delimbing knife set. (http://vmd.se/en/delimbing-kniveset/)

Another problem is in the knife mechanics. The attachment points of the knives are on a continuous strain from the pressure of the cylinders and the tree, deteriorating these points out in time. This causes the knives to move slightly at the attachment point, and in turn, produce diameter measurement data that is too narrow to the real diameter of the tree. Similar problem occurs also if the knives are dull and fail to delimb all the branches of the log, and get stuck between the stem surface and knives. Sensors start to produce too large diameter measurements and distort the trunk curve in the final tree report. Attachment point deterioration problem can be solved with replacing the bearings in the aforesaid places and recalibrating the sensors, and branch problem by re-running the log through the knives. (Lappi_2014), (Hamish et al. 2011)

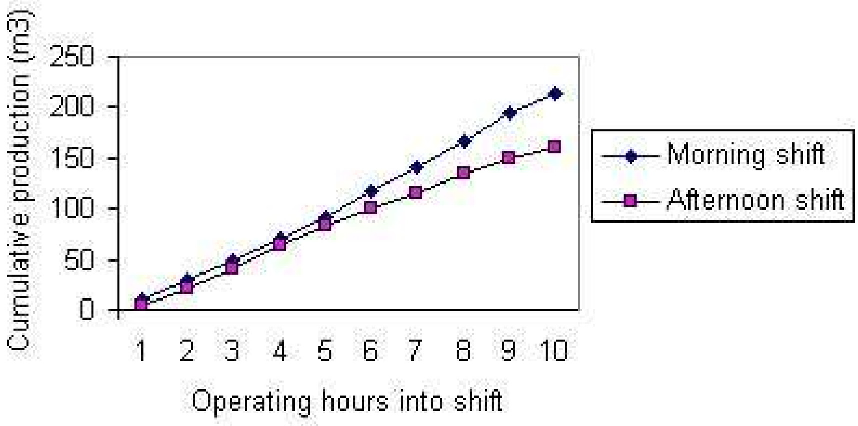
2.6.2.3 Feed rollers

Hölttä describes the feed roller mechanics and measurement in his study "*SOFT-SENSOR BASED TREE DIAMETER MEASURING*". It is written there that modern harvesters use these only to move trees through the harvester head, but older models used these to measure length or diameter of the logs. Diameter is measured by potentiometer –technology and length by hydraulic fluid flow sensor. (Hölttä, 2006)

However, it has been considered that length measurement data is unreliable and rarely used in modern logging, because the feed rollers get stuck easily during log processing due to the large branches or slip in an icy trunk during winter season. Also some tree species have naturally loose stem that causes slipping. All these factors cause feed rollers to produce log length data that is too big, compared to actual log length. This issue could possibly be solved using different kinds of feed rollers, such as threads or pair-rollers that have 2 rolls on each side, or increasing the compression pressure for the rollers. Nevertheless, calibration of the feed rollers is considered to be most effective. (Melkas & Visala 2009)

2.6.3 Factors affected by operator

In the study "*MENTAL STRESS ON HARVESTER OPERATORS*", Berger examined the psychological and physical stress factors that harvester operators face in their type of work in Austria. According to him, 72 percent of operators work 50-06 hours per week and have one lunch break during the day. Many employers courage their employee to not have coffee or smoking breaks, because it has negative effect on the productivity. However, it also greatly increases fatigue, which in turn causes stress and leads to lack of concentration. The end result varies, but it is considered that operator loses their productivity by 60 and bucking accuracy by 30 percent. (Berger 2003), (Nuutinen et al. 2008)



Picture no.16: Daily productivity averages for day and night shift. (Nichols, 2004)

Another article named "*Harvester Productivity and Operator Fatigue: Working Extended Hours"* by Andrew Nicholls and co. of Melbourne University described the correlation between fatigue and productivity and bucking accuracy. They stated that after 10 hours of work, operator begins to show signs of concentration deficiency, which affects the ability to detect defects in the assortments during processing. This means that the risk of producing logs with unacceptable defects increases with every extended working hour that operator experiences. (Nichols et al. 2004), (Nuutinen et al. 2008)

Conditions of the operator can be improved with modern technology and adjusting the working time to optimum, as suggested by aforesaid research article by Nicholls and co. Working the standard 9 hours per shift has found to be optimal amount of time when aiming for the minimal stress level of operator, as well as keeping the m3/h lumber production rate high. It also should be noted that having lunch break and short 5 minute breaks every hour greatly decreases the stress level of the operator and hence forth, affecting the measurement accuracy. (Nichols et al. 2004), (Nuutinen et al. 2008)

Some have considered the lack of operator training to be a factor with measurement accuracy but lately this has been proven wrong, as the automated length and diameter measurement still applies even with unexperienced operator. It is also reported that it affects hour-per-cubic meter productivity more than measurement data output. Only notable factor of untrained operator in measurement accuracy is the ability to detect error measurements produced by the sensors, but these are usually very easy to distinguish. (Nichols et al. 2004), (Nuutinen et al. 2008)

3. Methodology

3.1 Defining the scale of analysis

Forest harvester simulator offers more possibilities to explore with various parameter experiments without economic and time management issues. However, the data amount and scale of field measurements defined the scale of simulator work, as it was considered that data amount in both field measurements and simulator data output should be kept at same size for more reliable results in data comparison and analysis. Therefore the parameter experiments and number of trees felled in the simulated environment was also kept small. In addition, this John Deere simulator was capable of creating only three kinds of tree species, which limited the variability of simulator experiments to a certain degree.

Literary review revealed that measurement accuracy in harvesters are often in question. According to Kare (2015), CTL method has raised its popularity in global scale as a main logging method. Also, simulation of full tree- and tree length methods are more challenging to execute and the final data output would be again too excessive. Therefore it was considered logical to narrow this analysis to CTL method only. (Kare, 2015)

This analysis was conducted with collaboration of a research project IGA (stands for Internal Grant Agency) named *Nová metodika ověření přesnosti a spolehlivosti měření a kubírování dříví harvestory* (*New methods to verify the accuracy and reliability of measurement and scaling of forest harvesters*, in English) in Mendel University, which aims to develop and test methods that could be used to determine the factors that affect accuracy and overall reliability of harvester measurement systems and their data outputs on wood dimensions and volume. All the field measurement data acquired during the project was used in this analysis, as it was thought convenient way to save resources and time.

3.2 Data accumulation from field measurements

Field measurements were executed during 15-16.7.2016, in Czech Republic state forests near Rýmařov city. Forestry Company KATR a.s. worked as an collaborator, providing several services and equipment for the field work. This included harvester as a means to fell and process the measured logs and provide logging reports from all the assortments, forwarder for timber extraction and manipulation during image analysis and sawmill for image analysis, scanner measuring and sawmill sensor data.

Harvester Timberjack 1270D with Timbermatic 300 system was used to fell and process the trees in to assortments, which were referred *kulatina* as sawlog and *vláknina* as pulpwood. Saw logs and pulpwoods were processed in to four meter assortments. First felled tree yielded four saw logs and three pulpwood blocks, second tree four logs and one pulpwood and third tree four logs and three pulpwood. Volume of the trees varied between 1,75 and 1,02 cubic meters. Assortments were numbered in the butt end of the tree with different colors for better identification, which were measured in numerical order. Diameter was measured with tape and calliper in three sections, butt end, mid-section and top end, and recorded to paper. After manual measurement the logging report from the harvester was collected as a referential data source. Forwarder Timberjack 1110D was used to extract the trees from logging site to the forest access road, where they were individually placed in a metal frame to be photographed for the image and 3D scanner analysis.

Picture no. 17: Timberjack harvester processing the first target tree.

Produced assortments were transported to KATR Sawmill via log truck for sawmill scanner and 3D scanner measurements. Order of individual assortment measurements went as following:

1. Sawmill 2D scanning with bark intact
2. Debarking of all trees
3. Again 2D sawmill scanning, but without bark
4. 3D scanning, where only 6 logs were scanned
5. Manual measurement of all assortment logs with tape and calliper

Three dimensional scanner in question was Faro Focus 3D, and it recorded tree lengths, diameters and stem forms. All the data outputs were collected electronically after measurements.

3.3 Data accumulation from simulator research

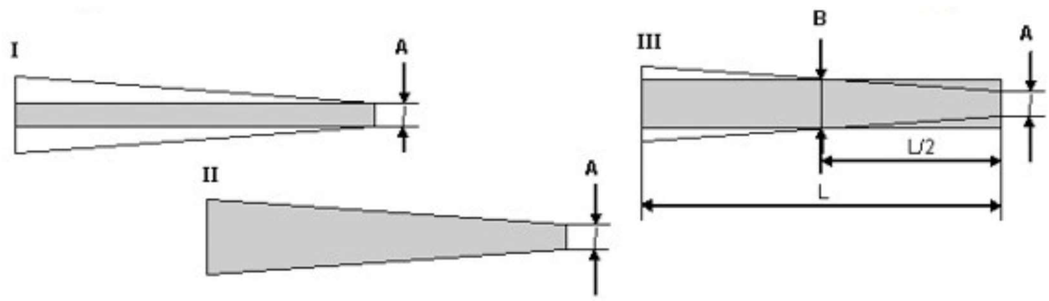
Simulator data experiments were conducted during August of 2016, in Mendel University, using John Deere 1270D simulator, with Timbermatic H09 software version. Purpose of this experiment was to select specific parameters in the O.B.C.S bucking settings and adjust them according to tree species being felled and each parameters individual characteristics, and finally analyze the data output change with every parameter experiment. Each time parameter was chosen, all the other bucking settings were set as *standard*, to avoid any data irregularities and to gain a point of reference. Standard bucking settings were as following:

- Price type - Kulatina was measured as m3toDE and vláknina as m3fUB
- Bark parameters – Bark parameters were not in effect
- Volume type – Kulatina was set to required length (cm) and vláknina as bucked length (cm)
- Diameter base curve – Standard diameter base curve (picture 21)
- Diameter measurement type – Over bark measurement

In addition, each time parameter was modified and tested in the simulated environment, one tree was felled with standard settings to gain point of reference. Logging report was also printed as PDF. The chosen parameters were considered to be most important to harvester measurement accuracy, and thought to produce the most variability in logging data output.

First parameter to be experimented with was Price type. It states the method to be used for estimate the volume of production in the bucking system. Values in the price matrix are stated as price/m3. There exists numerous of different types, but for this experiment most common price types were used:

- m3fUB – (Picture no. 18, figure II) Fixed volume, the volume is calculated as the true volume of the log. . (The volume is sectioned which means that the log is divided into 1 cm slices. The fixed volume is then reported as the sum of the volume of all slices.) Classification based on top diameter (A)
- m3toDE - (Picture 18, figure III). Volume (cylinder) and classification based on midpoint diameter (B), price due to small end diameter (A), HKS diameter. Diameter rounded downwards to the closest centimeter
- m3toUB – (Picture 18, fig. I). The volume is calculated as a cylinder with the top diameter of the log. Classification based on top diameter.(A)



Picture no. 18: Technical illustrations of three Price type volume calculation methods. (John Deere 2016)

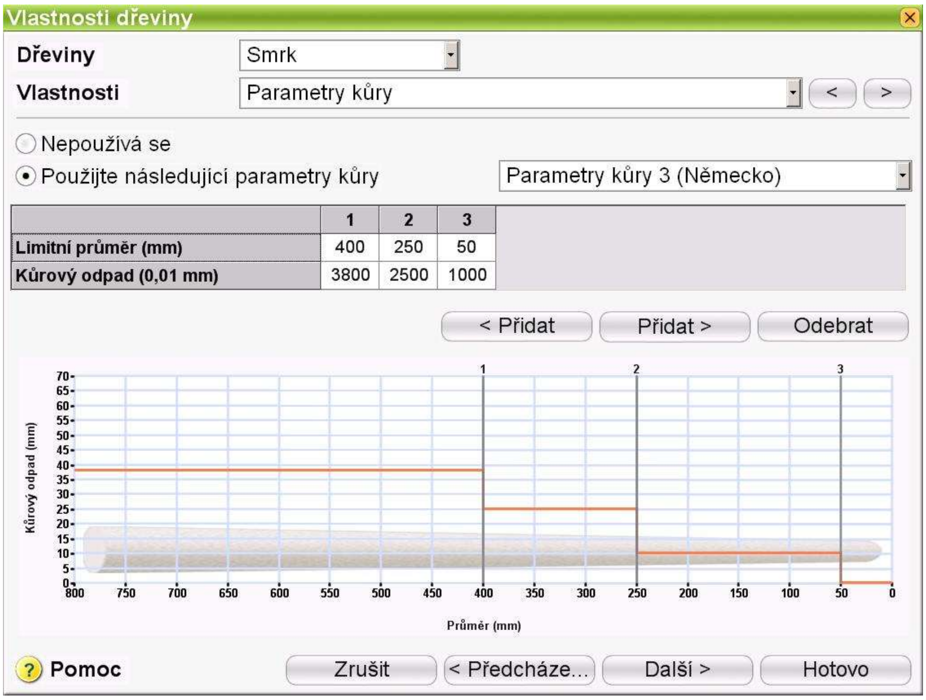
These three types were experimented with *kulatina* and *vláknina* assortments. Unlike the other parameter experiments, price types were tested out with single tree species, which was spruce. During data recording, these experiments were named "*Price type*" and numerically named according to the specific combination of assigned price types to *kulatina* or *vláknina* as such:

- Price type 1 – kulatina was measured as m3fUB and vláknina as m3toDE
- Price type 2 - kulatina was measured as m3toUB and vláknina as m3toDE

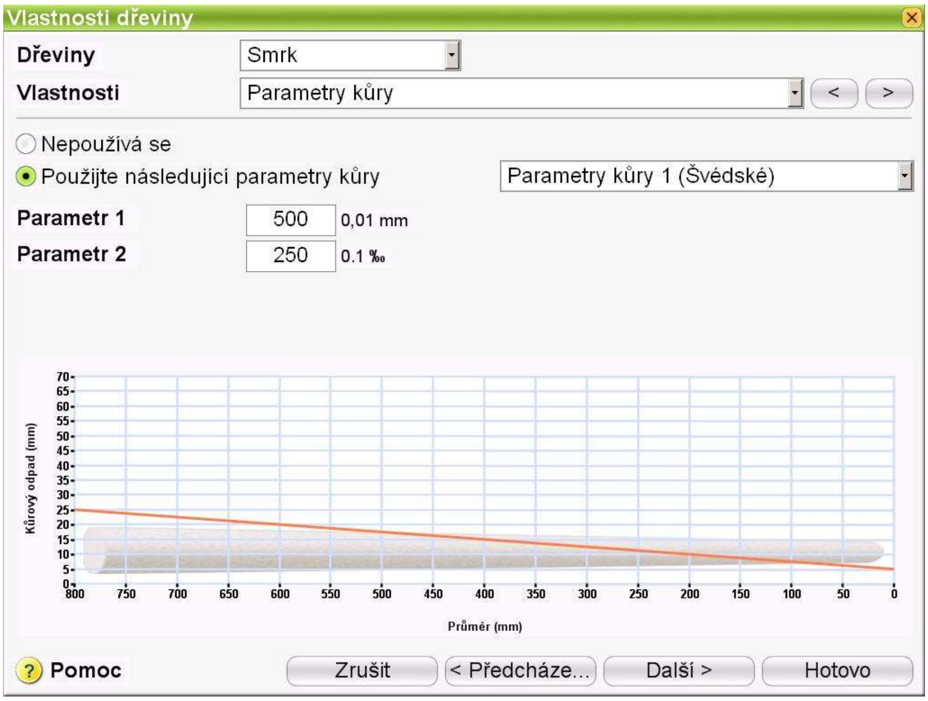
- Price type 3 - kulatina was measured as m3toDE and vláknina as m3toUB
- Price type 4 - kulatina was measured as m3toDE and vláknina as m3toDE
- Price type 5 - kulatina was measured as m3fUB and vláknina as m3fUB
- Price type 6 - kulatina was measured as m3toUB and vláknina as m3toUB
- Default - kulatina was measured as m3toDE and vláknina as m3fUB

Default experiment was considered as an point of reference to other price type experiments.

Bark parameters were chosen next. These are used for actual volume correlation without the bark, which in turn are used for payment calculations. Two kinds of bark parameters exist in the Timbermatic H09 system: Swedish and German. Both of these types hold two parameters, which both were adjusted to the realistic maximum and medium values in the settings, and experimented on for each tree species. Minimum values stood for standard data, as many companies do not utilize this bark parameter during bucking.



Picture no. 19: Bark parameter options screen 1



Picture no. 20: Bark parameter option screen 2

Swedish Bark parameter 1 - the size of bark deduction in diameter 0 cm (parameter * 0,01mm) and Swedish Bark parameter 2 - the slope of the straight line (parameter*0,1‰) Swedish pine maximum and medium values with bark parameters were set in experiment 1, 3500 and 1300, and for parameter 2, 200 in both. German pine max., and med. parameter values was with par.1 500 and 250 and par.2 400 & 200. Swedish spruce parameters were with par.1 250 & 200 and par. 2 200 & 100. German spruce parameters were with par.1 200 & 2000 and par.2 100 & 800. As with Deciduous trees, Swedish parameters with par.1 were 1000 & 500 and par.2, 100 in both. German deciduous parameters were set in par.1 150 & 2000 and par.2 300 & 1000. Experiment was narrowed again to 3 standard tree species (pine, spruce and deciduous) with one tree felling for each species. The experiment produced variable amounts of assortments depending on the diameter measurement change, therefore inserting all bark parameter data in to one diameter was not possible.

Third parameter was Volume types. These are used with a combination of price types to calculate the timber price in the bucking system. There are three volume types:

- Bucked length, cm; Uses the actual cutting length for production calculations.
- Required length; Reduces the over cut logs to the nearest length class

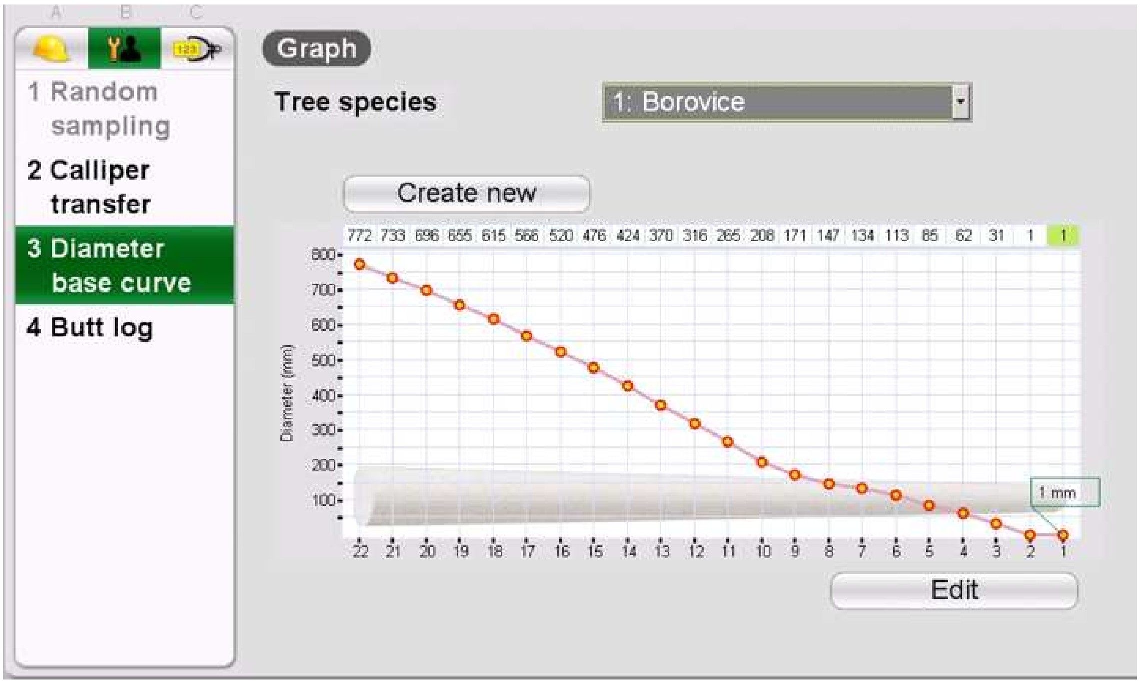
- Bucked length, in Decimeters; rounds down the over length logs to nearest decimeter

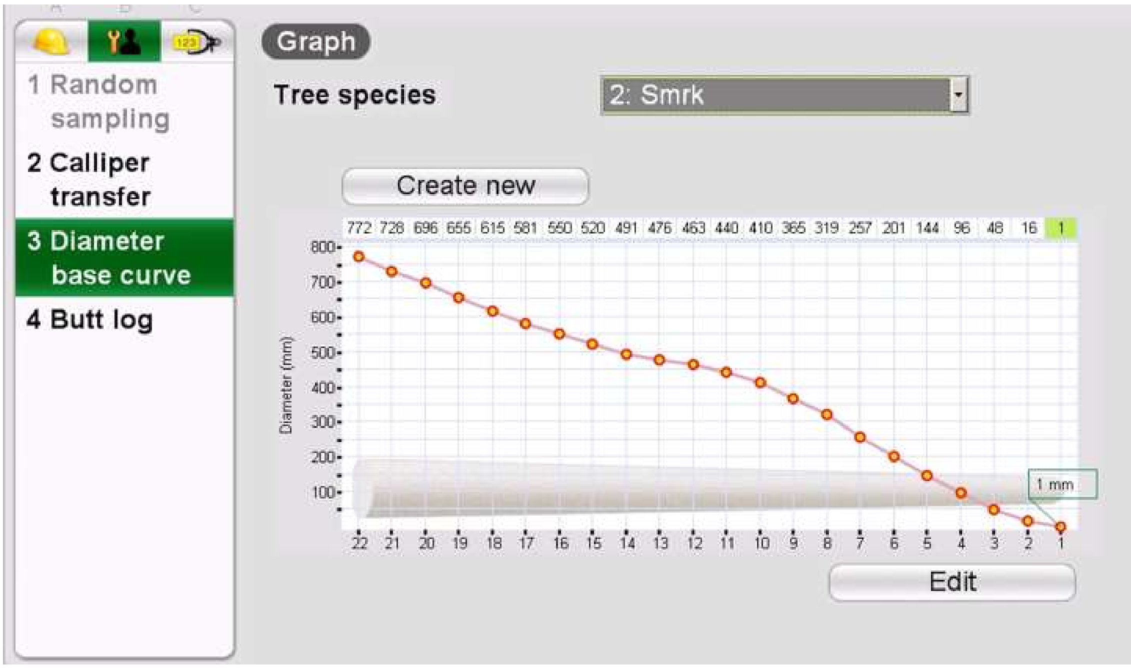
Fourth parameter was diameter measurement type, i.e., over and under bark parameters. Diameter measurement is normally set to over bark when bark dimensions are not known. If dimensions are known and defined in the system, the selections should be set under bark. For this experiment both under- and over bark diameter measurements were experiment for each tree species with single tree felling.

The fifth and final chosen parameter was diameter base curve. This parameter shows all the diameter values of the calibration points by tree species. Diameter calibration is done usually based on the measurement database in menu. There are five different methods for diameter calibration, but the base curve is used only with fifth method from the list below:

- Automatic: the operator accepts calibration proposal from the calibration wizard
- Manual: the operator changes the proposal for diameter calibration
- Default: the operator imports default values
- Factory: the operator imports factory settings
- Base curve: the operator changes base curve values

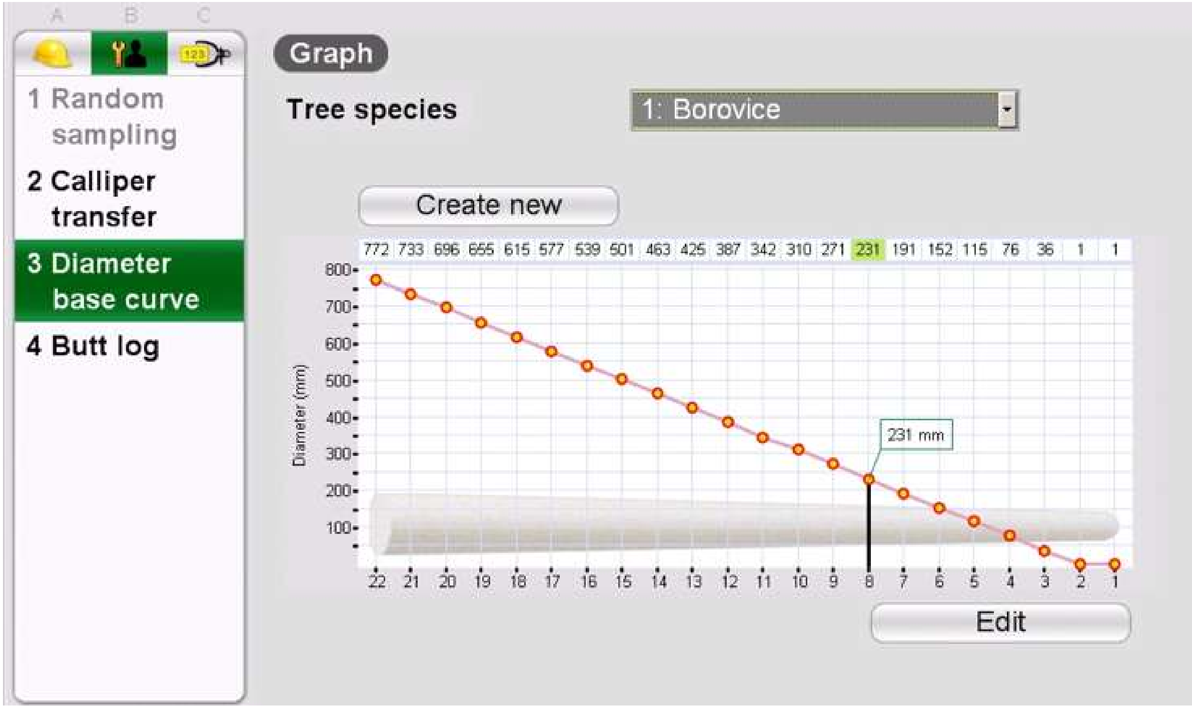
This curve is divided in to calibration points, which run numerically from right to left by specific diameter class (top vertical axis). These diameter classes can be set manually, but for this experiment the factory standards were used. Horizontal axis represents diameter in millimeters. As it is stated in the John Deere instructions manual, each calibration point's value should be adjusted five millimeters in maximum in one calibration event, to prevent any calibration errors. (John Deere 2016)





Picture no. 21 (upper) and 22 (lower): Screenshots of negative (upper picture) and positive (lower picture) calibration curves with pine and spruce.

Negative base curve (picture no. 21) was created by selecting the calibration point from the diameter class which was closest to the simulator tree diameter, and adjusted downwards 100 millimeters at maximum. Adjacent calibration points were adjusted negatively 10% less with each calibration point, until calibration curve reached 0% of adjustment in both high and low of the diameter class. This exact method was used in the positive diameter base curve adjustment. Standard data output was gained from standard calibration curve, set by the O.B.C.S. Standard calibration curve had maximum value of 772 millimeters, and minimum value of 36 millimeters. All the three calibration curves were tested on all three tree species.



Picture no. 23: Standard diameter base curve

Single tree was felled for each parameter setting experiment and tree species, with one size tree. This repetitive tree felling was possible with the simulator system's ability to recreate the previous felled tree in the simulation. In addition, only two kinds of assortments were ever produced to narrow research area: *kulatina* as saw log and *vláknina* as pulpwood. Simulated environment was set to "standard mixed forest", with apparent tree species being Norway spruce (*Picea abies [L] Karst)*, scots pine (*pinus sylvestris L*) and silver birch (*betula sp.*). Simulated tree diameter for each species ranged from 35-29 centimeters, and length 25-30 meters.

3.4 Reliability and accuracy of the results

During the data recording, many occasions may occur where the risk of these errors are present. Human, instrumental and observational errors are most strongly present during manual measurements, when fatigue or lack of knowledge cause most of the human and observational errors. However, instrumental errors may occur in the measurement instruments are not calibrated or are worn out.

As earlier stated, harvester measurement error can occur from multiple sources: logging site and nature conditions, harvester mechanics and sensors, and operator condition. During this field measurements with the harvester, site conditions were the lesser source of error. Visibility of the tree during processing was superb and the weather was overcast, which both of them have very little negative effect on the measurement event (picture 17). However, it is likely that the more significant error source could be the harvester's sensors. It was not known at time of tree felling and processing, what was the exact error percentage, but since Czech Republic standard demand of harvester error percentage is around 2, it is assumed that this was the case with this harvester. Only later analysis and data comparison will reveal the exact percentage.

Image analysis on the trees may involve human error and instrumental error. Human error can occur during individual assortment set-up, if the staff is not educated enough to know all the necessary steps, and photograph analysis with computer imaging software can produce same error as well, if the operating person is not educated well enough. Instrumental error can occur on the photographing device and the imaging software, if either of these are outdated. Sawmill poses the least expectancy of measurement errors, due to it having the most sophisticated and accurate technology from all the data sources of this analysis. Because of this, sawmill data is compared to all other data sources.

As this analysis relies on samples of different sources, it is subjected to reliability issues with its sample size. According to S.Marley from Select Statistics homepage, the size of samples dictates the amount of information it has, therefore partially determines the precision or level of confidence that it has in the sample estimates. An estimate always has some level of unreliability, which is dependent on the underlying variability of the data and the sample size. The more variable the data, the greater the uncertainty in the results. Similarly, the larger sample size reduces the level of unreliability of the results. It is also stated that the larger sample size often costs more time and money. In this analysis the sample size is relatively small with all the sources due to time and money constraints, hence the margin of error might be increase. Therefore it limits the statistical significance of the data to a degree, and the conclusions that are possible to draw from it. (Marley, 2014)

4. Results of analysis

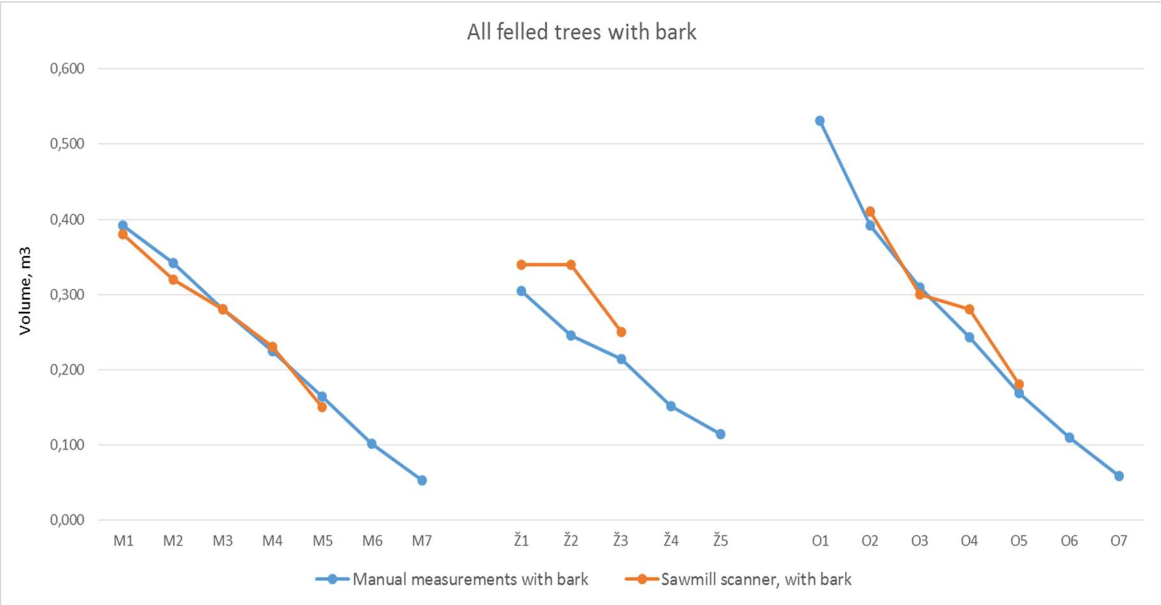
Strong emphasis on the results analyze was considering the mechanical-electronic devices measuring systems of harvesters, identify components and settings, which have the essential effect on the accuracy and reliability of timber measurement and scaling. Verification of this acquired knowledge both in practice and using the harvester simulator is the basic concept of this analysis.

According to the Timbermatic H-09 operator's instructions, harvester O.B.C.S houses over 20 individual and independently different parameters that affects assortment measurements majorly or to a minimal affect. These range from assortment options to harvester head options and from even individual felling site options. (John Deere 2012) Although all of these affect the measurement, and it would have proven to be interesting and lucrative to experiment and analyze each and every one of these parameters during this analysis, only six were selected which were thought to have the most effect in timber measurement. Also analyzing and presenting parameter experiment data with little or no change at all was considered not important.

Special emphasis was put in to parameters that have significant effect on volume estimation, but length and diameter measurement –related parameters were experimented upon as well. In case of length parameters certain factor restricted the full experimentation. This was the O.B.C.S cutting window –option, which directly restricts any excessive length measurement with any assortment type. It is essential when producing precisely cut assortments for sawmill, and disabling this feature was not considered to be reasonable, as it is almost never disabled during professional logging.

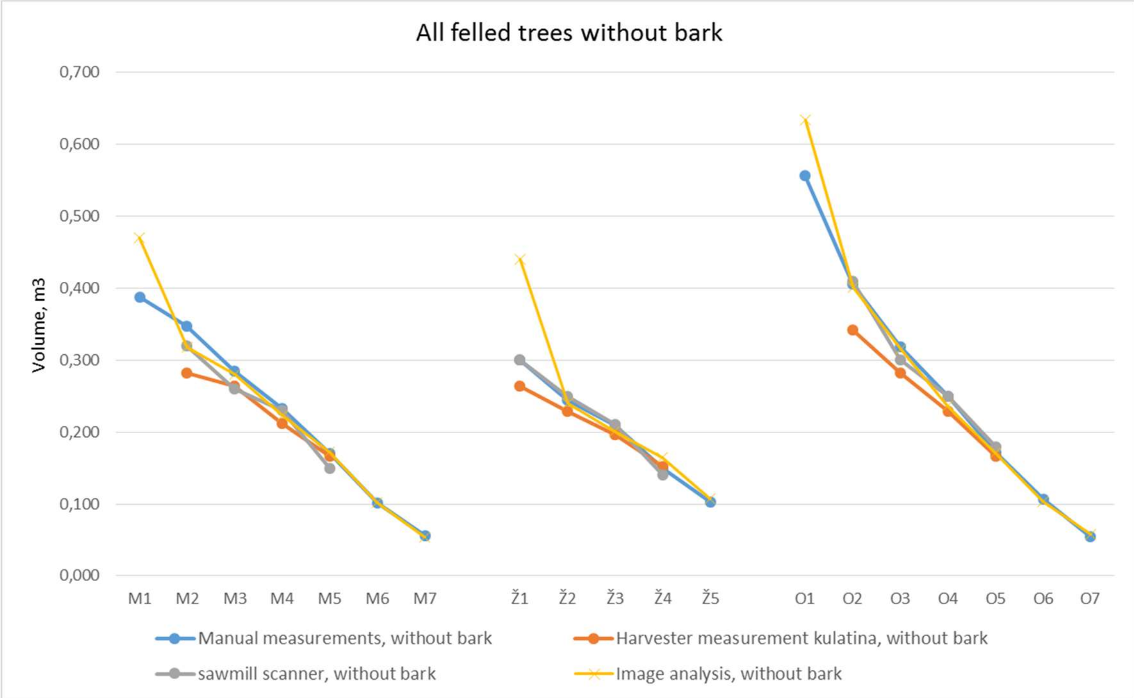
4.1 Variance of data with manual, harvester, image analysis, 3D scanning and sawmill measurements

Field measurements results can be divided to measurements with bark and without. Also most of the data was subjected to over-measuring, meaning all assortment logs were given extra length. This length addition is required as a reserve for subsequent processing. In the professional practice of Czech Republic, the volume of logs in the harvester is determined based on this intended length and mid-section diameter measurement over the bark. Pulpwood volume is calculated by the real length of the assortment, and again mid-section diameter.



Graph No.1: Field measurement results with bark intact.

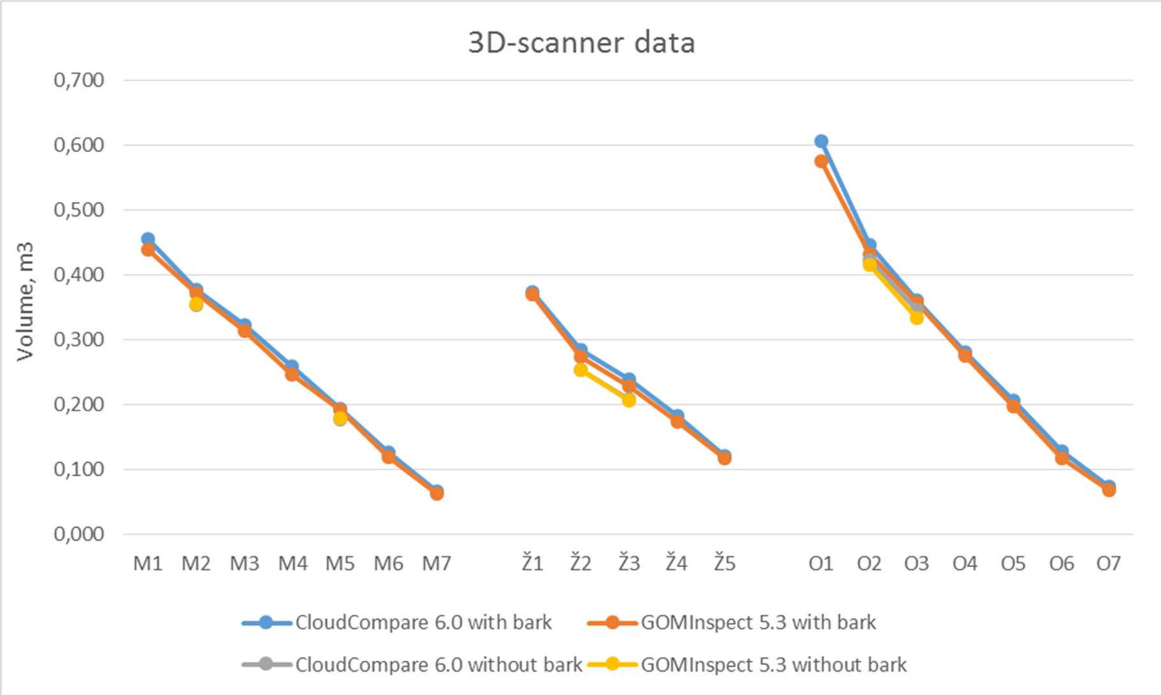
Graph 1 X-axis markings *M, Ž* and *O* present individual felled and measured trees, and numbering their processed order. Tree label *M* shows quite standard single tree volume distribution, but noticeable fact is the absence of sawmill scan measuring on the final two logs with every tree. This might be due to the fact that these assortments were either too narrow in diameter or too short in length to be included as an accepted dimensions of the sawmill qualifications. Tree *Ž* is the smallest one in size, as it produced only five assortments, whereas in *O* and *M* produced seven. Difference between sawmill and manual measurements is very noticeable, as *Ž2* assortments volume difference is **0,1** m^3, and *Ž1* **0,04** m^3. Tree *O* measurement data difference is bit less, however the first assortment was left out from sawmill measurement. Also *O4* has individual difference to other assortments, **0,04** m^3. It would have been ideal to compare field measurement methods to harvester measurement with bark intact, but unfortunately trees were measured with length addition in this exercise with harvester, and it was not considered to be compatible with data without length addition.



Graph No.2: Data from debarked trees.

Graph 2 shows the measurement results after tree debarking. As it was previously stated, most of the field measurement methods were aimed to be executed after debarking, hence the larger amount of measurement types after debarking. First assortment data in every tree is highly over measured by the image analysis and manual measurement method, with *M1* volume being **0,47** m^3, *Ž1* 0,44 m^3 and *O1* **0,63** m^3. This over measuring is most likely caused by expanded stem base (butt). Two final assortment data are absent with sawmill and harvester measurements in *M* and *O* trees. Additionally, same trees manual measurements with the first assortment are very high, with tree *M1* volume is **0,39** and *O1* **0,55** m^3. Despite the data spike with image analysis, this method and sawmill scanner data were the most identical.

Harvester measurement data had the trend of under measure almost every assortment of every tree, with volume data difference of sawmill and harvester being **0,04** m^3 on the average. This can stem from many factors, such as calibration, old harvester head hardware or other measurement –related parameters. Error percent of this particular harvester was not known before the felling event, so determining the cause is very problematic. Manual measurements are also prone to over-measure the diameter because of the expanded stem base.

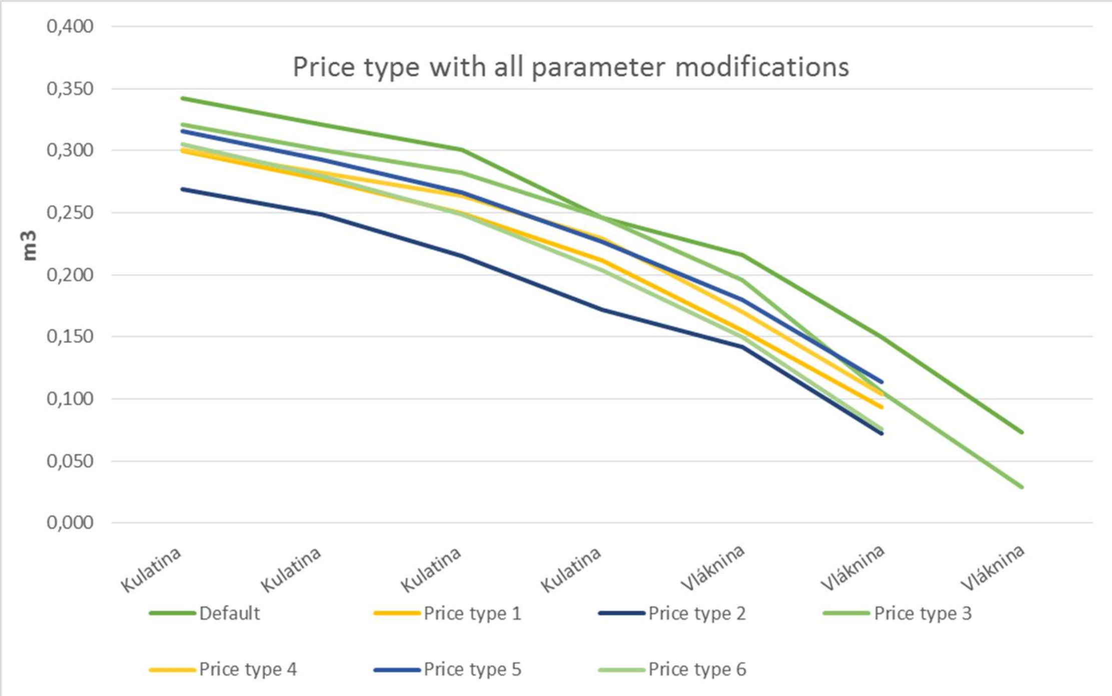


Graph No.3: Three dimensional scanner data results.

3D scanner data is shown in the graph 3. Scan data was processed with eight different software versions. Four measurements with 3DReshaper and MeshLab software systems were excluded, as they were too identical together to draw any individual conclusions or comments. As a whole, 3D scanner data is very identical. *GOMInspect 5.3 without bark,* and *CloudCompare 6.0 without bark* produced the boundary values (minimum and maximum). These scans measured only two assortments in every tree, with *Ž* and *O* the second and third and *M* second and fifth, and with a difference of some degree in assortment volume (varied between **0,03** and **0,01** m^3) It is unclear why this event occurred, but it can be considered that the cause is in the hardware capability. Also the Cloudcompare 6.0 with bark slightly over measured the first assortment in trees *M* and *O*, with **0,03** and **0,01** m^3 variance.

4.2 Simulator research

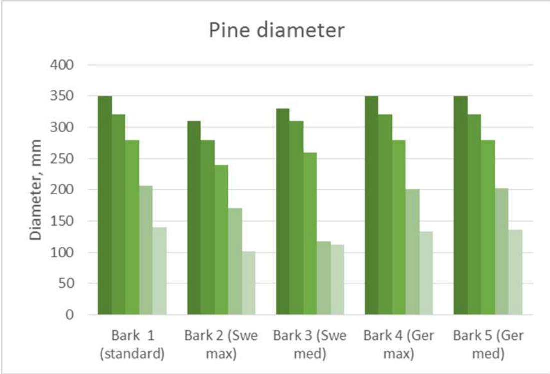
4.2.1 Price type

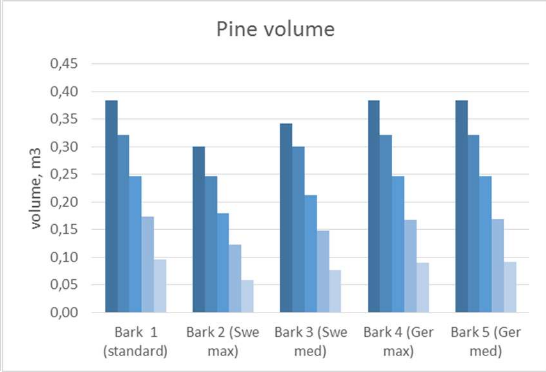


Graph No.4: Logging data changes with price type parameter modifications.

Graph number 4 shows data modifications in the tree volume. Default –line stands for default settings data, where no parameter modifications were made, with total tree volume of **1,649** m^3. From the chart we can see that to the default data, biggest output change was with Price type 1, which produced only two vláknina assortments and the total volume was **1,287** m^3. With price type 1 kulatina volume was measured as m3fUB and vláknina m3toDE, which might explain why this experiment produced so different results, because default data volume measurement was done with opposite price types. Smallest variation from the default data was with price type 3, with **1,481** m^3. This small variation might be due to the fact that kulatina was measured with same price type as was in default data, and vláknina was measured as m3toUB, which is similar to the m3toDE price type. Additionally, price type 3 and 4 share the same price type m3toDE, but have a different volume data, as price type 3 kulatina total volume being **1,346** m^3, and price type 4 total kulatina volume **1,076** m^3. The cause for this differentiation is unclear, as they should have at least similar volume data, but most likely this is caused by vláknina price type volume estimation influence, as they are different between price types 3 and 4.

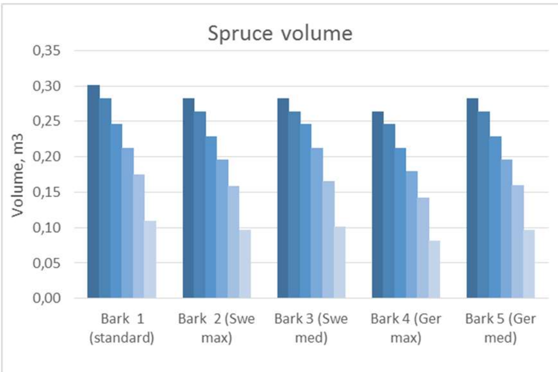
4.2.2 Bark parameters





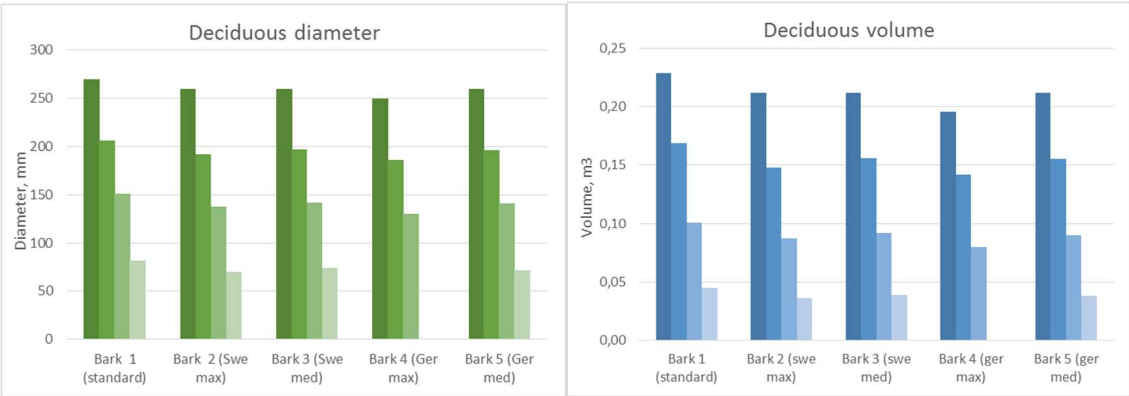
Graph No. 5 and 6: Pine diameter and volume data output with bark parameter changes.

Graph 5 and 6 presents pine volume and diameter according to their bark parameter changes. Most notable changes in the data was in diameter column Bark 3 with assortment no. 3 diameter being **118** cm, where other diameters in the same assortment were around **200** cm. This might be due to the fact that in this experiment, volume correlation is set to medium, which means that it does not apply so strongly to diameter measurement when compared to other measurements. Another significant change was in volume parameter Bark 2, where 1st and 2nd assortment difference to the standard volume was around **0,1** m3. This in turn again could be explained with volume correlation set to maximum, which causes the system to overestimate the bark layer, which in turn decreases the volume with every assortment. With both diameter and volume parameter experiments, German data produced virtually no changes with any bark parameter modification.



Graph No. 7 and 8: Spruce diameter and volume data output with bark parameter.

In the graph 7 and 8 we can see data output for spruce, in column charts. More or less surprisingly, there were very little change on any bark parameter experiment. This might be due to the fact that spruce has naturally quite thin bark, and by this volume correlation algorithms do not affect the diameter measurement or volume estimation so strongly, as it did with pine (graph 5 and 6). Diameter data is almost identical, excluding Bark 4 data. Volume data has slightly bigger data changes, as all of the Bark data are slightly skewed from standard. Highlight here is the Bark 4, but even there the differences between standard and Bark 4 are approximately **0,02** m^3.

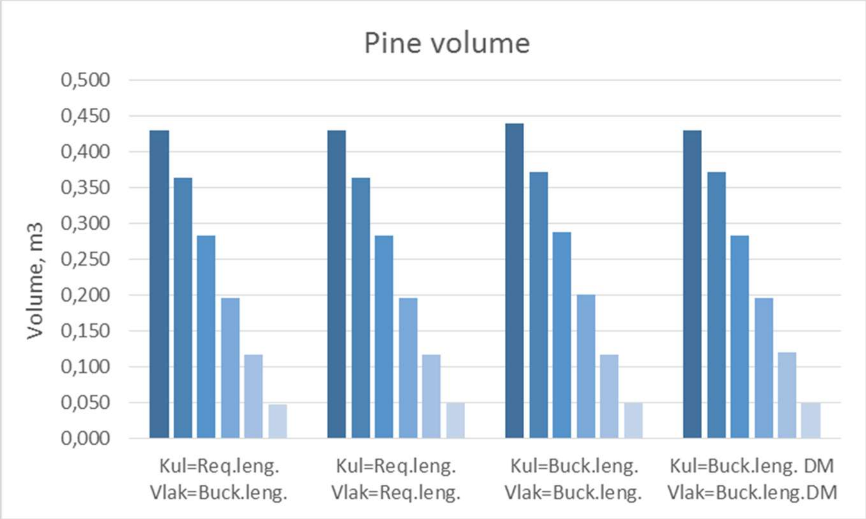


Graph No. 9 and 10: Deciduous diameter and volume data output with bark parameter.

With Deciduous data, similar small variability was detected as it was with spruce data. Only noticeable difference was the absence of 4th and final assortment in Bark 4 data. Here, final assortment's diameter was **130** mm and volume **0,08** m^3, which were almost double compared to other Bark data experiments. The absence might be explained to the minimum diameter limit of the vláknina assortment (70 decimeters), as the Bark 4 produced so narrow diameter measurement for said assortment, it was not suggested by the bucking system.

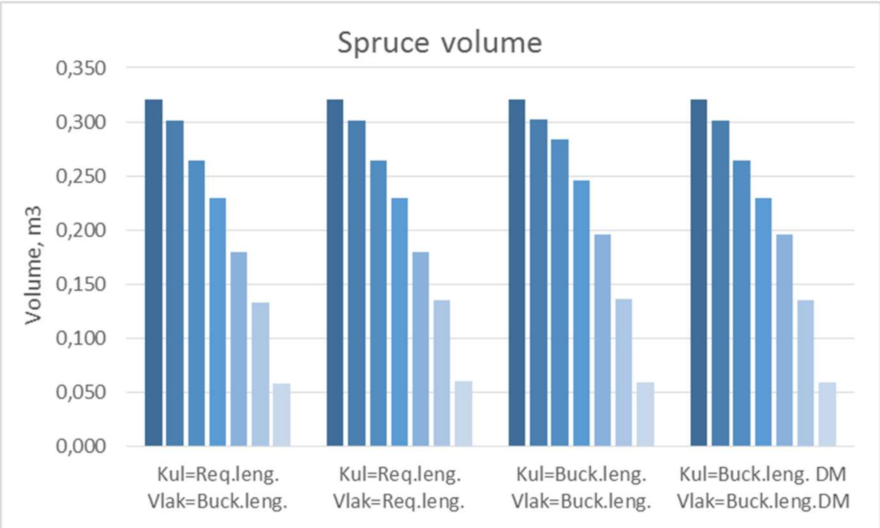
4.2.3 Length parameters – Volume type

Bucked length (cm), required length (cm) and bucked length (dm) parameters were experimented with one saw log (kulatina) and pulpwood (vláknina) assortments, producing four experiments times in three standard tree species. Total amount of experiments were therefore 12. All the other parameters were set to standard (see chapter 4.3). It should be noted that significant changes in length data could not be attained, as the cutting window in the bucking system restricts any excessive lengths outside of its preset window.



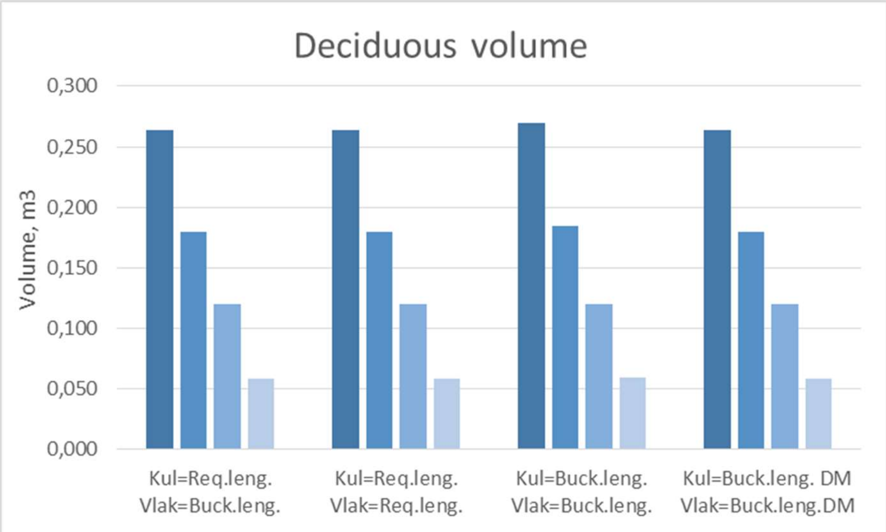
Graph No. 11: Pine volume parameter differences.

Graph 11 shows the pine volume data. As the previous experiments have stated, volume usually changes more than diameter or length. Diameter data did not change at all and length is not allowed to change due to the system limiting any length measurement irregularities with cutting window. Standard data (1st column) volume is **1,434** m3 and 3rd **1,462** m3.



Graph No. 12: Spruce volume data.

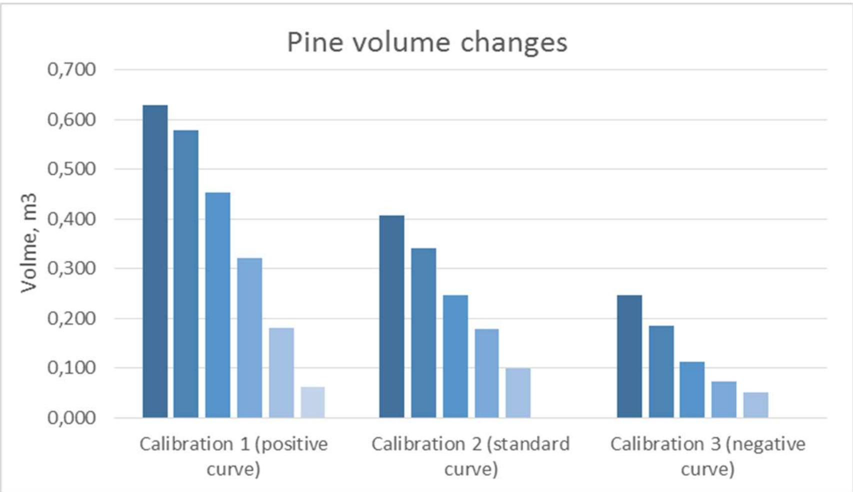
Graph 12 presents spruce volume data. As it was with pine, spruce assortment volume differences between experiments were very little. Total tree volume was with standard data (first column) **1,490** m3, and 2nd **1,486** m3, 3rd **1,544** m3 and 4th **1,505** m^3. Second column produced the lowest data overall, and it was expected due to the required length setting, which measures the tree length without added length measurement. Length data for spruce produced virtually no changes in any experiment, and thus was not deemed enough to be presented.



Graph No. 13: Deciduous volume data.

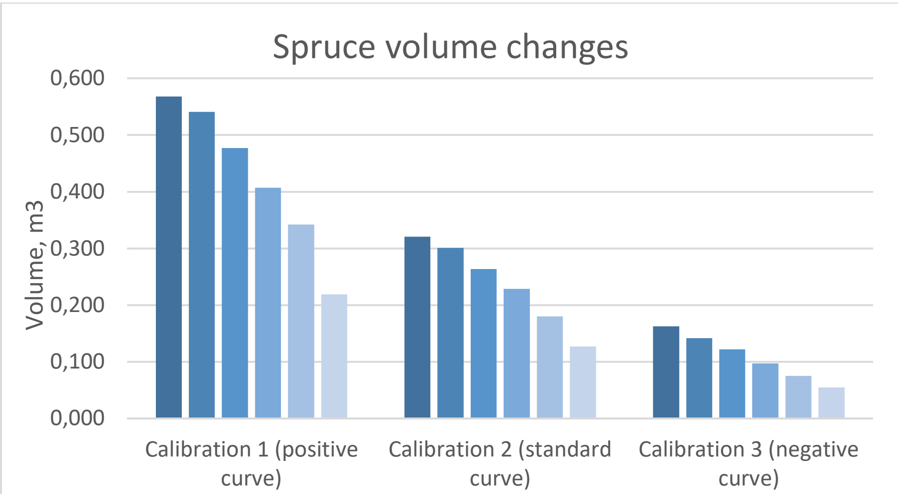
Deciduous data output is near identical to that of pine and spruce, as it can be observed from graph 14. Only slight change was in the 3rd assortment (3rd column), with total volume being **0,634** m^3 and standard data **0,622** m^3. This might be due to the fact that length addition to the nearest length class did not add any excessive length to the assortments, thus not producing any over estimation of the volume. Length data was exactly the same in every experiment.

4.2.4 Diameter base curve - Calibration



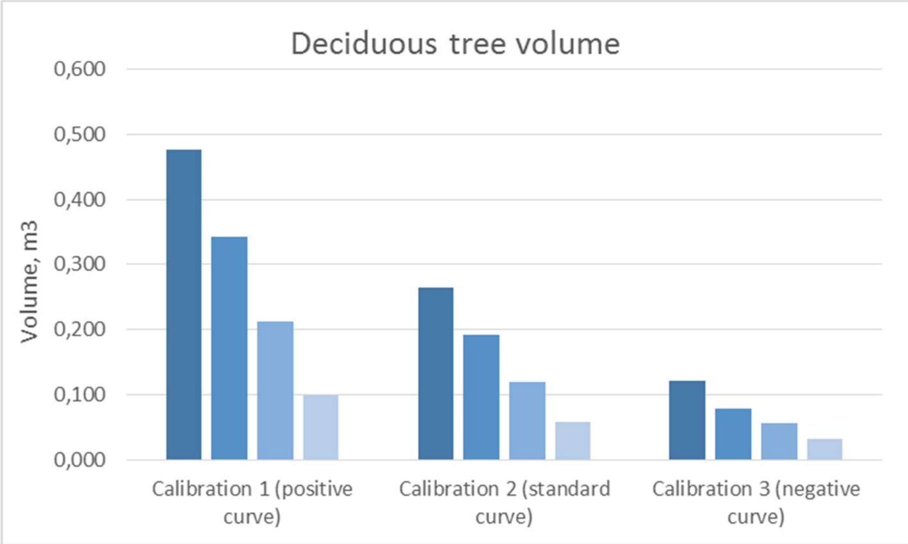
Graph No. 14: Pine diameter base curve data output with standard and modified curves.

Graph 14 shows the calibration curve experiment for pine. Standard curve data total volume was **1.273** m^3, calibration 1 volume **2,225** m^3 and calibration 3 had **0,665** m^3 of volume. It is obvious that when the diameter measurement system is manually adjusted to over-measure, the results will be variable. In this case the positive curve over-measured the log diameters so excessively, that it allowed to bucking system to produce one extra assortment (sixth column on calibration 1). Overall the positive curve over-measured every assortment more than negative curve under-measured, meaning that most of the assortments in calibration 1 is **0,2** m^3 bigger than standard assortment. Negative curve's assortments are **0,15** m^3 smaller than standard data, so there is a **0,05** m^3 overall difference in over- and under measurements. All these changes were expected, but not with such power.



Graph No. 15: Spruce diameter base curve data output.

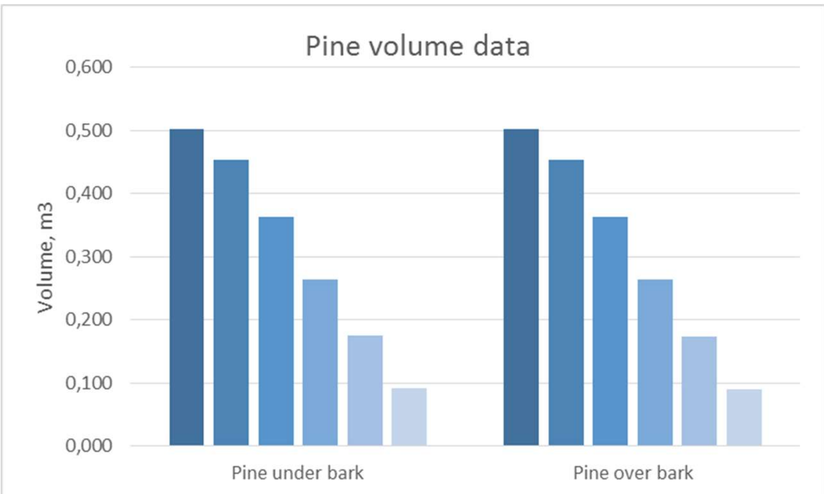
Spruce data experiment is shown in the graph 15. Standard curve data total volume was **1,422** m^3, calibration 1 volume **2,554** m^3 and calibration 3 had **0,654** m^3 of volume. Unlike pine experiment, spruce experiment did not produce one extra assortment during the calibration 1 experiment. Overall differences between all the data are slightly greater than the differences in pine experiment, but the cause for this is not clear. It might be due to the base curve's diameter classes, which were slightly more numerous than with pine diameter classes. More classes means more calibration points, which in turn means that the effect of base curve modification is stronger. This experiments seems to have a trend when the diameter of assortment is bigger, so are the volume differences as well. Log assortments in calibration 1 are **0,25** m^3 greater and calibration 3 logs are only **0,15** m^3 smaller.



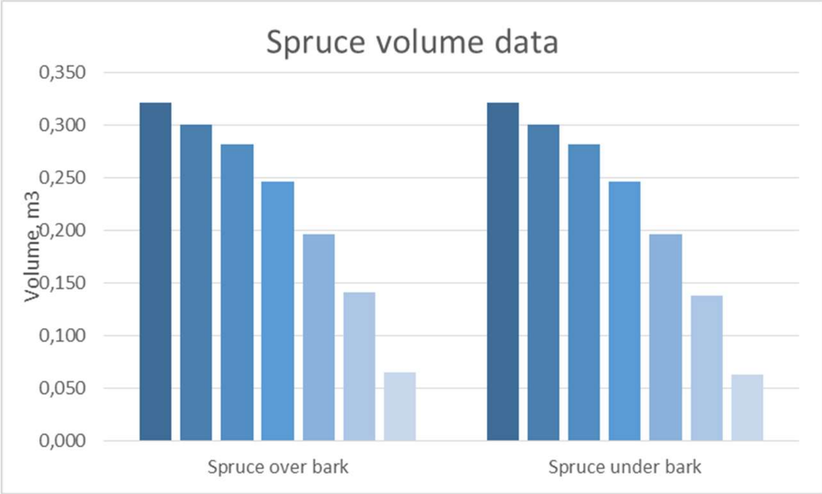
Graph No. 16: Deciduous volume data output.

Graph 17 illustrates the deciduous tree data variability. Standard curve data total volume was **0,632** m^3, calibration 1 volume **1,130** m^3 and calibration 3 had **0,286** m^3 of volume. The trend is similar to the spruce and pine volume changes, positive curve over-measured more than negative curve under measured, although the volume differences are slightly smaller. Cause for this could possibly be the same as with spruce, but inverted. As deciduous tree had less calibration points, the effect caused by modification is smaller. Calibration 1 over measured around **0,2** m^3, and calibration 3 under measured around **0,11** m^3.

4.2.5 Diameter measurement type – Under and over bark



Graph No. 17: Pine volume data changes with over- and under bark diameter measurement.



Graph No. 18: Spruce volume data changes.

Graphs 18 and 19 shows the results from all of the tree species. It is quite obvious that no significant changes was in the data. Only experiment that produced change in the first place was pine, with under bark total volume was **1,552** m^3 and over bark volume **1,547** m^3. Spruce and deciduous produced virtually no change in the data, which was surprising. This may be caused by the bucking systems over and under barks algorithms, which may be set so low, that trees of this size will not produce any changes, but with larger trees the changes of the data might be visible.

5. Discussion

Tree quality and quantity estimation is common topic in modern forestry. Research efforts for these estimate improvements are more focused on laser scanning technology and remote sensing, so comparison studies of 3D scanner and other timber measurement methods were scarce and problematic to find. However studies from Kalmari et al. (2011) and Acuna & Murphy (2007) showed that 3D scanning can be much more accurate then harvester head triangulation method, as it can effectively recognize stem form defects and other aspects. However the scanning technology cannot address the issue of woods internal structure aspects or defects, and adding to the fact that 3D scanner is hard to deploy in the harvester head or slow to be used individually during logging. Also the cost of such device may prove to be too much for harvester entrepreneur to purchase. However, if the scanner could be integrated in to the harvester head and O.B.C.S, it could have the potential of drastically increasing timber scaling and measurement accuracy.

As the 3D scanner may be important factor in future harvester technology, it is necessary to acknowledge the fact that harvester mechanics and software are not the only factor in the measurement accuracy. Several studies such as from Nichols et al. (2004), Ovaskainen (2009) and Pulkkinen (2009) revealed that operator fatigue, dense under canopy layer and weather changes affect timber measurement and quality estimation greatly. All of these factor have their own individual means to combat this issue, but they should still be taken in to account when implementing or designing new technology.

The measurement data of trees with bark suffered from insufficient data issues. Harvester using under-bark measurement setting and the trees being debarked afterwards at the sawmill, did not give the opportunity to measure them with over-bark setting. Adding to the fact that harvester used the length addition method during assortment processing, comparisons between measurement methods with bark were not accessible. Possibility of using 3D scanner and image analysis was also discarded due to the time and cost issues during field measurements. Adding to the fact that sawmill left out several assortments from measuring reduced the data size even more. However, it was known at the start that field measurements will focus more on the de-barked tree measurements, rather than trees with bark. The data itself with manual and sawmill measurement was slightly erratic, with no detectable or deducible trends in the data distribution.

As stated before, 3D scanner was highly accurate measurement method, but due the over measuring of the length, data had to be analyzed separately from other measurement methods. This over measuring data existed also with other measurement methods, it was considered better to analyze the data with length of the trees. The 3D scan data with software systems 3DReshaper and MeshLab were the most identical. CloudCompare and GOMInspect data without bark was curiously measured with only one or two assortments per tree, whereas data with bark exists with every assortment, due to the time issues mentioned before. Because sawmill did not use this over measuring method, accuracy comparison between 3D scanner and sawmill data was not possible

In the case of over, or under bark tree measurement, there are several issues to address to. Some of the O.B.C.S bucking algorithms are built to estimate the bark layer thickness for every tree species to improve volume estimation, as bark is removed with most cases when tree is processed in to various product. Sawmills may require this logging data under bark rather than with the bark. Also some tree species possess very thick bark layer, which volume might be difficult to estimate, even by the harvester bucking system, whether measurement of trees should be done with bark or without is dependent on the tree species, the equipment of the sawmill or general working method of a country or region. There is no clear “yes” or “no” answer.

Harvester simulator as a research tool has been used in earlier researches for time and productivity studies, as well as work ergonomic and technique studies, but this kind of system parameter experimentation and analysis is possibly first of its kind. After thorough research I was unable to find anything related to harvester measurement parameter studies dedicated on simulated environment. Studies such as *Operator's physical workload in simulated logging and timber bucking by harvester*, by Dvořák et al. (2016), and *Comparison of Harvester Work in Forest and Simulator Environments* by Ovaskainen (2005) proved that simulator environment is ideal for different kinds of researches, which in real life might have risks of system and hardware damage occurrence or be expensive studies to conduct with an actual harvester. As Ovaskainen stated in his study’s discussion section:

“*These results also indicate that simulators can be used for research purposes when differences from reality are controlled. The number of changing variables is limited, and certain aspects of the harvester work can be separated for more detailed study.*”

This can also be applied to this study, as “*controlled reality”* in this study is presented as parameter modifications and test felling in simulated environment. Adding the fact that harvester simulator environment can be modified to the needs of the research or educational event, and also in case of system errors the whole simulator can be reset and rebooted, although purchase cost of these forest machine simulators are often very high (around 75 000 €).

Combining these two types of measurement analysis may seem bit disorientating, as each of them have their own characteristics, factors and goals, but for this analysis it seemed like meaningful to combine them together, as both of them are connected to measurement improvement. When comparing field measurements and simulator experiments, field measurements was more widespread with several measurement methods and work phases. I think simulator experiments were more narrowed in theme and required more thorough research to gain knowledge of the system and parameters so that the selection of the most suitable parameters and sufficient scale of the experiment could be done. Data collection, processing and analysis was quite similar with both works. Although no groundbreaking revelations or conclusions could not be able to draw from either off these experiments, this experiment is not useless.

Both of these works laid grounds to future research opportunities. One such opportunity could be more thorough research on the simulator, with more sample trees, tree species and different tree sizes during simulated felling, and more parameters to experiment with. This would allow for more comprehensive conclusions to be drawn from the results with bigger sample size and variability. This larger research scale would also enable to develop more intricate and complex bark algorithms for under bark tree estimation, and completely new algorithms to combat such issues as measurement errors caused by seasonal changes. Another possibility could be linking the field measurements straight to the simulated environment. Uploading the field measurement tree data in to the simulator environment via 3D scanning could enable straight comparison between different field measurement methods and harvester parameter experimentations. As the field measurements could provide the point of reference, simulator research with different parameters could enable to observe first-hand, which parameter modification decreases or increases that situational error percentage of the harvester. At best, the simulator can be important player in the field of harvester productivity and reliability studies.

6. Summary

When debarked sawmill measurement data is considered the most accurate and is the point of reference for the rest of the data, image analysis and 3D scanner were most accurate with volume difference between these being less than **0,01** m^3 with every measured assortment (however the image analysis produced one over-measured data with every logs first assortment). With the 3D scanner data, the maximum value of the assortment volume with 92 percent of cases was with program CloudCompare, the minimum value of the assortment volume, and 80 percent of the cases with GOMInspect program. The differences between the maximum and minimum volumes of individual assortments ranged by a few percent, the median was 4.3 percent. The share of bark on the volume of individual assortments amounted to an average of 7 percent. It also should be noted that some assortment barks were infested with bark beetle. As stated before, harvester measurement seems to produce the lowest values and manual measurement the highest. Reasons for harvester under measurement are various, as it can be dependent on system settings, calibration or others. As for manual over measurement, most likely reason is the measurement error caused by measurer.

Image analysis method was measured to calculate the volume slots and the front face of the pin. These areas had difference depending on the tape. Sawmill discarded 7 of 19 assortments, due to incorrect length addition. According to the harvester logging report, the average share of bark in total volume was 8.6 percent (from 7-8 percent for the first five assortments to 13 percent by assortments from the top part of the stem). Manual measurement of the diameter of the individual assortments before and after debarking at least brought us satisfactory results in comparison to all used methods. In this measurement method in comparison with other methods at high risk of errors caused by the activities of persons conducting measurement. Large role to play here especially the experience of using this method in practice.

Simulator experiment data distribution was overall homogenous in terms of what parameter was altered and what was the expectancy was from the data output. Out of the all parameters, price type and diameter base curve yielded the most change in tree measurement data, whereas volume type and under- and over bark parameters had very little change. Interestingly every price type experiment caused the simulator system to exclusively underestimate the volume of every assortment. It would seem that even though there exists numerous of different methods of assortment volume estimation, these three particular price types assigned to kulatina and vláknina- assortments tends to underestimate the volume constantly. However, price type experiment was unique experiment compared to others, due to the fact that only spruce tree was used as a data source. It is hard to tell if the data from other tree species (pine and deciduous), or if the other price types (such as *m³fmi* or *m³miDE*) excluded from this analysis would still underestimate the volume.

Diameter base curve is the most complex one from all the other experiments. Where other parameters use specific kind of algorithms to execute the parameter, diameter base curve directly adjusts how the triangulation method measures the diameter. Adding to the fact that most adjustment to the calibration points was set to the diameter class that was most close to the actual and pre-set BHD-diameter of the simulated trees. Therefore it is not a surprise that this experimentation yielded one of the most changes in volume data output distribution. Pine and deciduous volume data change with both calibration curves was 30-35 percent from the standard data, where spruce volume changed 40-50 percent. This kind of safe and resettable simulator environment is ideal for this kind of risky experimentation, where in the real harvester system risks of system error or permanent damage are always present.

As thesis objective is split in to two objectives, they were reached. As for the field measurements, image analysis and 3D scanner proved to be most accurate measurement methods. Harvester measurement was slightly more erroneous, as the *error percent* for all the trees was **5,4**. This does not allow do draw any conclusions however, as the error percent is usually determined with dozens of calibration trees (John Deere 2012) and this field measurement event was using three trees and total of 19 assortments. As for the simulator work objectives, diameter base curve and price type parameters proved to be the most influential parameters of timber volume and diameter estimation, as diameter base curve directly affects the diameter measurement and price type volume calculation. Other parameters affected the estimation by some degree, but most of these parameters were restricted by other parameters during the experiment, so more variable results could not be obtained.

7. Závěr

Měření odkorněného dříví na pile je považováno za nejpřesnější metodu zjišťování rozměrů a je referenčním bodem pro ostatní data. Obrazová analýza snímků a 3D skenování byly nejpřesnějšími metodami s rozdílem menším než 0,01 m^3 u každého měřeného sortimentu (obrazová analýza snímků však nadhodnotila data u všech oddenkových výřezů). Maximální hodnoty objemu výřezů poskytoval v 92 % případů program CloudCompare, minimální hodnoty objemů výřezů pak v 80 % případů program GOMInspect. V 64 % případů bylo minima objemu výřezů dosaženo ve verzi programu FaroScene 5.3, verze programu FaroScene 6.0 přispěla k dosažení maximální hodnoty objemu výřezu v 68 % případů. Rozdíly mezi dosaženými maximálními a minimálními objemy jednotlivých výřezů se pohybovaly v řádu procent, medián činil 4,3 %. Podíl kůry na objemu jednotlivých výřezů činil průměrně 7 %. Jak je uvedeno výše, výsledkem měření za použití harvestoru jsou nižší hodnoty a při použití ručního měření vyšší hodnoty. Příčin podhodnocování veličin harvestorem je mnoho, protože měření je závislé na systémovém nastavení, kalibraci a dalších faktorech.

Elektronická přejímka pily vyřadila z 19 manipulovaných výřezů 7 kusů (37 %) do nižší evidované délky kvůli chybnému nadměrku. Podíl kůry na objemu jednotlivých výřezů byl v porovnání s měřící metodou 3D skeneru zaznamenán podstatně nižší, k této skutečnosti však přispěla manipulace výřezů na OM a v areálu pily hydraulickým jeřábem a čelním nakladačem, kde docházelo ke ztrátám kůry stržením. Dle výrobního výkazu harvestoru činil průměrný podíl kůry na objemu zpracovaných výřezů 8,6 % (od 7 - 8 % u prvních pěti výřezů až po 13 % u výřezů z korunové části kmene). Tato skutečnost je ale dána spíše nastavením redukčních koeficientů kůry v měřícím systému harvestoru než opakovaným měřením téhož výřezu v kůře a bez kůry jako tomu bylo u elektronické přejímky na pile. Ruční měření průměru jednotlivých výřezů před a po odkornění nám podalo nejméně uspokojivé výsledky ve srovnání se všemi použitými metodami. V 58 % případů byl průměr kmene po odkornění identifikován jako vyšší než při měření v kůře. U této měřící metody je v porovnání s ostatními metodami vysoké riziko chyb způsobených činností osoby provádějící měření. Velkou roli zde hrají zejména zkušenosti s použitím této metody v praxi.

Data z experiment na simulátoru byla celkově homogenní vzhledem k měněným parametrům a předpokládaným výsledkům. Ze všech parametrů měly největší vliv na změnu dat cenový typ a křivka průměrů kmene, zatímco typ objemu a měření s kůrou a bez kůry ovlivnily data jen minimálně. Zajímavým zjištěním byla skutečnost, že každý z experimentů s cenovými typy vyústil v podhodnocení objemů všech sortimentů. Přestože existuje řada různých metod kalkulace objemu sortimentů, tyto 3 druhy měření cenových typů přiřazených ke kulatině a vláknině objem konstantně podhodnocují. Experiment s cenovými typy je nicméně jedinečný v porovnání s ostatními experimenty v tom, že data byla měřena jen na smrku. Je obtížné stanovit, zda by při použití dat z měření jiných druhů dřevin (borovice a listnaté) či jiných cenových typů (jako m^3fmi nebo *m3miDE*) stále docházelo k podhodnocování objemu.

Křivka průměrů kmenů je nejkomplexnější z provedených pokusů. Tam kde ostatní pokusy využívají konkrétní typ algoritmu k provedení parametru, křivka průměrů kmenů přímo upravuje způsob, jakým triangulační metoda měří průměr. V průběhu tohoto pokusu byla křivka záměrně zvýšena nad doporučený limit 5 mm na kalibrační bod a kategorii průměru se záměrem zjistit, do jaké míry toto ovlivní výsledná data. Většina úprav kalibračních bodů byla navíc nastavena na nejbližší a přednastavenou kategorii průměru simulovaných stromů. Proto není překvapivé, že výsledkem tohoto pokusu byly největší změny v distribuci dat. Objemová data pro borovici a listnáče byla změněna v případě obou kalibračních křivek o 30-35 procent a smrk o 40-50 procent v porovnání se standardními daty. Toto bezpečné a opětovně nastavitelné prostředí simulátoru je ideální pro tento typ riskantních pokusů. Při použití skutečného harvestoru vždy hrozí riziko systémových chyb či trvalého poškození.

Cíle této diplomové práce byly rozděleny na dvě části, a dle mého názory byly splněny. Co se týče terénních měření, analýza snímků a 3D skenování byly nejpřesnějšími metodami měření. Pracovníci provádějící tato měření je nicméně považují za časově náročnější (nebyla však provedena časová studie). Měření harvestorem bylo o něco méně přesné. Míra chybných měření pro všechny stromy byla 5,4 procenta. To však neumožňuje dojít k žádnému závěru vzhledem k tomu, že procentuální chyba je normálně určena ze sady mnoha kalibračních stromů a pro toto terénní měření bylo použity pouze tři stromy a celkem 19 sortimentů. Co se týče mých zjištění při práci na simulátoru, bylo určeno že parametry křivky průměru kmene a cenového typu mají největší vliv na měření průměrů a kalkulaci objemu dříví. Ostatní parametry do určité míry také kalkulaci ovlivnily, ale většina těchto parametrů byla omezena jinými faktory a nebylo tak možné zjistit variabilnější výsledky.

8. References

ACUNA, M.A., MURPHY, G.E., 2007 Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas fir. [cit. 2016-09-06] Bosque Volume 28, Issue 3. Pages 187-197

BEMBENEK, M., MEDERSKI, P. and KARASZEWSKI, Z. 2014 [cit. 2016-09-07] Length accuracy of logs from birch and aspen harvested in thinning operations. Turkish Journal of Agriculture and Forestry 39. Available from: https://www.researchgate.net/publication/280314367_Length_accuracy_of_logs_from_birch_and_aspen_harvested_in_thinning_operations

BEGER, C. 2003 [cit. 2016-09-09] MENTAL STRESS ON HARVESTER OPERATORS. Institute for Forest and Mountain Risk Engineering. Vienna, Austria. Available from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.543.9387&rep=rep1&type=pdf

CHIORESCU S. & GRÖNLUND A. 2011 [cit. 2016-09-06]. ASSESSING THE ROLE OF THE HARVESTER WITHIN THE FORESTRY-WOOD CHAIN. Forest Products Journal. Volume 51, number 2. 2000

DOOLEY, T. & NIEUWENHUIS, M. 2006 [cit. 2016-09-14]. The Effect of Calibration on the Accuracy of Harvester Measurements. International Journal of Forest Engineering, Volume 17, Issue 2, Pages 25-33. Available from: http://www.tandfonline.com/doi/abs/10.1080/14942119.2006.10702533

electrical4u.com - ONLINE ELECTRICAL ENGINEERING STUDY SITE. 2011 [cit. 2017-02-10]. Errors in Measurement | Classification of Errors. Available from: http://www.electrical4u.com/errors-in-measurement-classification-of-errors/

DOOLEY, T., LAYTON, T. and NIEUWENHUIS, M. 2006 [cit. 2016-09-14]. The impact of calibration on the accuracy of harvester measurement of total harvest volume and assortment volume for Sitka spruce clearfells in Ireland. Available from: file:///C:/Users/Ilari/Downloads/2177-1967-1-PB%20Dooley%20Layton%20Nieuwenhuis%2063%201&2%202006%20(1).pdf

EUROPEAN COMMITTEE FOR STANDARDIZATION – CEN. 2005. [cit. 2017-01-21] Round and sawn timber - Method of measurement of dimensions - Part 2: Round timber - Requirements for measurement and volume calculation rules. Technical Committee CEN/TC 175. Available from: http://www.avih.nl/pdf/prEN1309-2.pdf

HAARLAA, R. 1992 [cit. 2016-09-21] ORGANIZATION AND TECHNOLOGY OF WOOD HARVESTING IN FINLAND. Department of Forest Resource Management, University of Helsinki, Finland. Available from: http://www.fao.org/docrep/w2809E/w2809e06.htm

HAMISH, M., GLEN, M. & BOSTON, K. 2011 [cit. 2016-09-09]. Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands. Canadian Journal of Forest Research 36(7). Pages 1661-1673.

HÖLTTÄ, V. 2006 [cit. 2016-09-06]. SOFT-SENSOR BASED TREE DIAMETER MEASURING. Engineering Laboratory, Helsinki University of Technology, Finland

INNOVAWOOD PORTAL. Module 2: Timber measurement and calibration. [online]. 2006 [cit. 2016-09-06]. Available from: http://77.74.50.56/Innovawood/DesktopDefault.aspx?tabindex=15&tabid=163

Jiří Dvořák et al. 2011 [cit. 15.1.2017]. THE USE OF HARVESTER TECHNOLOGY IN PRODUCTION FORESTS. Kostelec nad Černými lesy. Available from: https://www.researchgate.net/publication/272401111_The_use_of_harvester_technology_in_production_forests

JOHN DEERE MEASURING AND CONTROL SYSTEM PRODUCTS HOMEPAGE [online]. 2016 [cit. 2016-09-05]. Available from: https://www.deere.co.uk/en_GB/products/equipment/measuring_and_control_systems/timbermatic_h09/timbermatic_h09.page

JOHN DEERE TIMBERMATIC H-09 OPERATOR'S INSTRUCTIONS. 2014 [cit. 2016-09-21]. Worldwide Construction and Forestry Division, John Deere. Published in Finland.

JOHN DEERE TIMBERMATIC MEASURING AND CONTROL SYSTEMS – COMMERCIAL AND EDUCATIONAL BROCHURE. 2012 [cit. 2016-09-07]. Available from: http://colheitademadeira.com.br/wp-content/uploads/publicacoes/246/Timbermatic%20Measuring%20and%20Control%20Systems.pdf

KALMARI J., KULOVESI J. & VISALA A. 2011 Measuring Log Length using Computer Stereo Vision in Harvester Head. [cit. 2016-09-06] Proceedings of the 18th World Congress. The International Federation of Automatic Control Milano (Italy) August 28 - September 2.

KARES, E. 2015. Puunkorjuun koneellistuminen – Kehityspolku. Development of Finnish forest technology. [cit. 2017-01-18]. TEKES reviews 304/2015. Available from: https://www.tekes.fi/globalassets/julkaisut/puunkorjuun_kehityspolku304_2015.pdf

KARÈL, J. Round Wood Measurement System. 2012 [cit. 2016-09-06]. Mendel University. Faculty of Forestry and Wood Technology. Czech Republic.

KOMATSU MaxiXplorer CONTROL AND INFORMATION SYSTEM COMMERCAIL BROCHURE. [online] [cit. 2016-09-05]. Available from: http://shop.mediahandler.se/pdf/partek/kMaxi_b_gb.pdf

KORPILAHTI, A., HUJO, S. and POIKELA, A. Katkontatarkkuuden ylläpito hakkuukoneilla (in eng. Upkeeping the forest harvester cutting accuracy). 2006 [cit. 2016-09-05]. Raport published by Metsäteho Oy Helsinki. © Metsäteho Oy. Available from: http://docplayer.fi/11056730-Katkontatarkkuuden-yllapito-hakkuukoneilla.html

LAPPI, J. Testing of the Ponsse Opti6 Measuring System. 2014 [cit. 2016-09-06]. Bachelor Thesis. Degree Programme in Information Technology. Oulu University of Applied Sciences

LINDBLAD, J. Puutavaran Mittaus (Timber Measurement). Tapion Taskukirja. 2008 [cit.2017-01-20]. Tapion Taskukirja (Tapio's Pocketbook of Forestry). Published by Reseach and Development Center Tapio.

NORDLIE A., STAFFAL T., 2015 [cit. 2016-09-06]. Head-Mounted Displays for Harvester Operators – A Pilot Study. Master of Science Thesis. Industrial Engineering and Management. SE-100 44 Stockholm.

NICHOLS, A., BRENN, L. and HUMPHREYS, N. 2008 [cit.2016-09-09]. Harvester Productivity and Operator Fatigue: Working Extended Hours. Journal Article. Available from: https://journals.lib.unb.ca/index.php/ijfe/article/view/9850/9989

NIEUWENHUIS, M. & TADH, D. 2006 [cit. 2016-09-06]. The Effect of Calibration on the Accuracy of Harvester Measurements. International Journal of Forest Engineering. Volume 17, Issue 2.

NUUTINEN, Y., VÄÄTÄINEN, K., HEINONEN, J., ASIKAINEN, A and RÖSER, D. 2008 [cit.2016-09-09] The Accuracy of Manually Recorded Time Study Data for Harvester Operation Shown via Simulator Screen. Silva Fennica research articles, Finland.

MASSER CORPORATION HOMEPAGE – HARVESTER HEAD CALIBRATION. 2016 [cit. 2016-09-07]. Available from: http://www.masser.fi/solution-items/harvester-head-calibration/

MELKAS, T. & VISALA, A. 2009 [cit. 2016-09-09]. Hakkuukoneella kerätyn mittaustiedon hyödyntäminen. Journal of Forest Sciences. Metla, Finland.

MARLEY, S. 2014. [cit. 2017-02-11]. The Importance and Effect of Sample Size. Select Statistical Services Blog. Available from: https://select-statistics.co.uk/blog/importance-effect-sample-size/

MURPHY, G. Worldwide experiences with mechanisation and value recovery. 2003 [cit. 2016-09-16]. Proc. Of the Wood for Africa 2002 Conference, Pietermaritzburg, South Africa.

OVASKAINEN, H., 2009 Timber harvester operators' working technique in first thinning and the importance of cognitive abilities on work productivity. [cit. 2016-09-06] Academic dissertation. Faculty of Forest Sciences. University of Joensuu

PONSSE HARVEST SYSTEM PRODUCTS [online]. 2016 [cit. 2016-09-05]. Available from: http://www.ponsse.com/products/information-systems/forest-machine-systems/harvester-systems

PONSSE SATUNNAISOTANTAMITTAUS – EDUCATIONAL BROCHURE. 2016 [cit. 2016-09-05]. Available from: http://www.puuhuolto.fi/omavalvonta/wp-content/uploads/Ponsse_Satunnaisotantamittaus.pdf

PULKKINEN, M. The affect of the temperature when mechanically measuring the length of a tree trunk. 2009 [cit. 2016-09-09]. Bachelor thesis. Mikkeli University of applied sciences, 2009. Available from: https://www.theseus.fi/bitstream/handle/10024/5570/Opinnaytetyo.pdf?sequence=1

PONSSE Opti4G COMMERCIAL BROCHURE. [online] 2015 [cit. 2016-09-05]. Available from: http://www.ponsse.com/content/download/3876/111658/file/PONSSE_Opti_2015_ENG.pdf4

RITCHIEWiki. 2009 [cit. 2016-09-21]. Harvester – Forestry equipment. Available from: http://www.ritchiewiki.com/wiki/index.php/Harvester

ROTTNE OFFICIAL HOMEPAGE, FORESTRY MACHINERY PRODUCTS. [online] 2016 [cit. 2016-09-05]. Available from: http://www.rottne.com/en/skogsmaskin/rottne-h-11/?description

ROTTNE HARVESTER COMMERCIAL BROCHURE. [online] 2015 [cit. 2016-09-05]. Available from: http://www.rottne.com/wp-content/blogs.dir/1/files_mf/1432649138Broschyr_skordare_2015_en.pdf

SIROHI, R.S., & Radha Krishna, H.C. 1991 [cit. 2016-09-09]. Mechanical measurement. 3rd ed. INTERNATIONAL (P) LIMITED, PUBLISHERS. New Delhi. Available from: https://books.google.cz/books?hl=fi&lr=&id=A5PCmGteqlsC&oi=fnd&pg=PR5&dq=Sirohi,+R.S.,+and+Radha+Krishna,+H.C.+1991.+Mechanical+measurement.&ots=4FnyxbOZhg&sig=jSTDPD4WbYN4bTxuog3ZzYYtCy4&redir_esc=y#v=onepage&q=Sirohi%2C%20R.S.%2C%20and%20Radha%20Krishna%2C%20H.C.%201991.%20Mechanical%20measurement.&f=false

SLADEK, P. & JINDRICH, N. 2007 [cit. 2016-09-07]. ANALYSIS OF VOLUME DIFFERENCES IN MEASURING TIMBER IN FORESTRY AND WOOD INDUSTRY, Meeting the Needs of Tomorrows´ Forests – New Developments in Forest Engineering, October 7 – 11, 2007, Vienna and Heilegenkreuz – Austria. Available from: https://www.formec.org/images/proceedings/2007/session_9_pdf/9_1_paper_sladek_neruda_austro_formec_2007.pdf

SONDELL, J., MOLLER, J.J., and ARLINDER, J. 2002 [cit. 2016-09-15]. Third-generation merchandising computers. SkogForsk, Uppsala, Sweden. SkogForsk Results 2.

StanFord homepage – Skogforsk. 2014 [cit. 2017-01-17]. Available from: http://www.skogforsk.se/english/projects/stanford/

StandFord2010. 2010. [cit. 2017-01-18]. Modern communication with forest machines – Informative PDF. Available from: http://www.skogforsk.se/english/projects/stanford/

STRANDGARD, M. & WALSH, D. 2012 [cit. 2016-09-15] Assessing measurement accuracy of harvester heads in pine plantation operations. CRC for Forestry Technical Report no. 225.

SUURINIEMI. E. John Deere's G-Series harvesters and forwarders – More than a machine. INTERNATIONAL FOREST INDUSTRIES MAGAZINE. October 2015. Available from: http://internationalforestindustries.com/2015/10/john-deeres-g-series-harvesters-and-forwarders-more-than-a-machine/

Ústav pro hospodářskou úpravu lesů Brandýs nad Labem (UHUL). 2015.[cit. 3-4-17] ZPRÁVA O STAVU LESA A LESNÍHO HOSPODÁŘSTVÍ ČESKÉ REPUBLIKY V ROCE 2015. PDF available from: stazeni/informace-o-lese/zelene-zpravy-mze