Estimating the accuracy and time consumption of a mobile machine vision application in measuring timber stacks

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Highlights

- The machine vision-based mobile Trestima Stack application was a more accurate and faster measuring method than a conventional stacked timber measurement.
- The measurement difference of Trestima Stack had a better average in large terminal yards (+0.6%) than at roadside landings (+4.5%).
- For both measurement methods, there was a negative correlation between the stack size and the volume-based effective total measurement time consumption.
- Trestima Stack can be recommended for inventorying timber stacks at roadside landings, particularly when the stacks measured consist of several measurement batches.

Abstract

Trestima Stack is a mobile application innovated by Trestima Ltd. It is based on machine vision, which measures the volume of a timber stack from images taken by a smartphone or a tablet device. The aim of this study was to determine the accuracy (i.e. measurement difference) and effective measurement time consumption of the Trestima Stack application compared to a conventional stacked timber measurement method. Research data consisted of a total of 60 timber stacks, of which 32 were measured in terminal and intermediate yards and 28 at roadside landings. The control volumes of the stacks were measured in September 2016 – January 2017 at the Stora Enso Anjala, Imatra and Varkaus mills by hydrostatic weighting. The total control volume of pulpwood in the study was 11,957 m^3 solid over the bark (m^3). Across all study data, the accuracy of Trestima Stack averaged +2.7%. In large terminal yards, accuracy was better (+0.7%) than at smaller roadside landings (+4.5%), whereas with the conventional stacked timber measurement method, the measurement accuracy was at a similar level in terminal yards (–4.8%) as at roadside landings (–4.9%). There was a statistically significant difference between the measurement methods used in measurement accuracy. The most common reason for inaccuracy with the Trestima Stack application was empty space in the final image framing around the stack. The average effective total measurement time consumption with Trestima Stack was 10.6 s/m^3, while it was 13.7 s/m^3 with the conventional stacked timber measurement method. For both measurement methods, there was a statistically significant negative correlation between the stack size and the volume-based effective total measurement time consumption. On the basis of this study, the Trestima Stack application can be recommended for inventorying timber stacks at the roadside landings, particularly when the stacks measured consist of several measurement batches.

Keywords: machine vision; image analysis; timber inventory; mobile measuring; stacked timber measurement.

1. Introduction

Timber measurement plays an essential role in controlling the wood procurement process, as well as in steering raw material production, timber book-keeping and inventory management. Timber stacks are inventoried periodically and inventory volume is compared to the quantity of accounting. When inventorying timber stacks in Finland, the volume of timber has traditionally been measured using a method of conventional stacked timber measurement.

There are both short and longer-term timber storages. Short-term timber storages are utilized during the season of bad roads when decentralized timber storages are unattainable, and in the summertime breakdowns when mills do not receive the timber (Lindblad, 2008). Short-term timber storing is aimed at smooth wood supply logistics. Correspondingly, longer-term storages in terminals will secure the wood deliveries of the mill in the event of a surprising occurrence. At roadside landings, timber is typically stored for a short time, while at intermediate and terminal yards with large-sized timber stacks, wood is stored for a longer time.

In Finland, the current Timber Measurement Act (414/2013) (Laki puutavaran, 2013) entered into force in 2013. The Act regulates the measurement of timber harvested in Finland. The purpose of the Act is to specify the measurement methods for unprocessed timber and ensure equipment performance and the reliability of measurement results. Moreover, the Ministry of Agriculture and Forestry in Finland revised the more detailed Decree of measuring methods for timber measurement and the use of measuring instruments (Maa- ja metsätalousministeriö, 2013). The Decree specifies the accuracy requirements for the volume measurement of timber formations. The official conversion factors of different measuring methods are given by the Order of Natural Resources Institute Finland (Luonnonvarakeskuksen määräys, 2017).

When the conventional stacked timber measurement method is used, firstly the length, height and width of a stack are manually measured. Subsequently, the gross volume of the stack is calculated by multiplying the length by height and width. Next, the solid volume percentage for the stack is determined by estimating the stack content factors: 1) the mean diameter of logs, 2) branchiness and delimbing of logs, 3) crookedness of logs, and 4) stacking of logs (Kuitupuun pinomittaus, 2003; Luonnonvarakeskuksen määräys, 2017). Finally, the gross volume of the stack is converted to net volume by multiplying the gross volume of the stack by the solid volume percentage. Currently, used stack content factors, as well as their classes and effects (i.e. correction percentages) on a solid volume percentage, are based on big datasets of several stacked timber measurement studies in Finland (Heiskanen, 1973a; 1973b; Heiskanen and Salmi, 1975; Nikkilä et al., 1975; Kärkkäinen, 1978; Kärkkäinen and Salmi, 1982; Sairanen, 1995).

In the conventional stacked timber measurement method, when the stack measured is high, i.e. more than 2.5–3.0 meters, the measurement of height is less accurate than that of lower stacks (Heiskanen, 1973a). Therefore, the instructions for the conventional stacked timber measurement suggest that the maximum stack height measured is 3 meters (Kuitupuun pinomittaus, 2003). In addition, when the stack is longer than it is high, i.e. the stack has a great ratio between its length and height, the influence of the measurement error in the height measurement of the stack is very significant (Heiskanen, 1973a). In order to minimize the measurement error of the stack height, it is recommended to divide the stack into sections of one or two meters (cf. Kuitupuun pinomittaus, 2003; Meyen and O'Connell, 2012; SDC´s instructions, 2014) which means that only the risk of the measurement error of stack width (i.e. the length of logs in a stack) is considered significant (Sairanen, 1995).

The timber assortments are cut into either an approximate length, whereby at least 90% of the logs cut must be within ±10% of the given length by harvesting instructions, or a fixed length, with a corresponding accuracy of ±1% (Kuitupuun pinomittaus, 2003). In reality, it is difficult to accurately determine the stack width since, in addition to the different length of logs in the stack, the pulpwood stack may also consist of short butt logs from a log section of a stem and the top logs of cutting with subsidiary length measures (Heiskanen, 1973a; Sairanen, 1995). Furthermore, in the conventional stacked timber measurement method when measuring pulpwood with a length of more than 3 meters, accurately determining the stack net volume is challenging because the stack content varies considerably with long pulpwood (Sairanen, 1995).

When the stacks inventoried are big and there is a large amount of wood in many separate stacks, the conventional stacked timber measurement method takes a considerable amount of time. Consequently, the conventional stacked timber measurement method has fairly high measuring costs (Lindblad, 2008).

The most common method for measuring pulpwood at pulp and paper mills in Finland is a weight sampling, where first the timber is weighed, following which the volume of wood bundle is determined with a green density (Melkas, 2018). Mostly, weighting at the mill is carried out by a bridge scale and the green density of the wood bundle is obtained by weighting the wood bundle and immersing it into a measuring container (Hokka and Vuorenpää, 2001).

Nowadays, timber measurement is one of the most rapidly progressing areas in the forest industry (Lindblad et al., 2012). In Finland, the potential for new technologies is being emphasized, for instance in papers such as Visions of Timber Measurement Research and Development and Efficient Wood Supply 2025 (Hämäläinen et al., 2006; Rajala et al., 2015; Niemelä et al., 2018). In these vision papers, novel technology is focused on, in particular a machine vision and image and signal processing, analysis and modelling.

There are several definitions for the term Machine Vision. For instance, Snyder and Qi (2010) determined it as follows: Machine vision is the process whereby a machine automatically processes an image and reports "*what is in the image*", as well as recognizing the content of the image. Furthermore, Snyder and Qi (2010) stated that machine vision includes two components: 1) a measurement of features and 2) a pattern classification based on those features. On the other hand, Davies (2012) defined Machine Vision as consisting of methods, techniques and hardware whereby artificial vision systems can be constructed for practical applications. These kind of applications can be utilized, for instance, in automatic inspection, and robot and process guidance in industry, or for security monitoring (e.g. Hornberg, 2006; Beyerer et al., 2016).

There are a great number of research publications and conference papers wherein methods detecting the volume of stacked timber have been tested and demonstrated in the last ten years (e.g. Gutzeit et al., 2011; Gutzeit and Voskamp, 2012; Noonpan and Chaisricharoen, 2013; Herbon, 2014; Herbon et al., 2014; 2015; Knyaz and Maksimov, 2014; Shvarts and Tamre, 2014; Galsgaard et al., 2015; Chiryshev and Atamanova, 2016; Kruglov, 2016; 2017; 2018; Pásztory and Polgár, 2016; Kruglov and Chiryshev, 2017; Kruglov and Shishko, 2017; Kruglov et al., 2017a; 2017b; 2017c; Mehrentsev and Kruglov, 2017). In the European market, there are currently seven commercial machine vision-based mobile measuring applications for the measurement of stacked timber and logs at roadside landings or in terminal yards:

1) AFoRS,
2) Fovea,
3) HD Silva,
4) Logsize,
5) sScale,
6) Timbeter, and
7) Trestima Stack.

The sScale system has been innovated by the Dralle A/S company, and is mounted on the roof of a car (Made to measure, 2015; sScale, 2018). The rest of the applications listed are mobile tools for smartphones and tablet devices (AFoRS, 2018; Fovea, 2018; HD Silva, 2018; Logsize, 2018;

Timbeter, 2018; Trestima Stack, 2018).

The Finnish technology company Trestima Ltd has developed a machine vision-based mobile Trestima Stack application (Trestima Stack, 2018). Trestima Stack is a tool for measuring the volume of a timber stack from images taken by a smartphone or a tablet device. With Trestima Stack, the user measures the stack with a one meter reference stick attached to it. Machine vision identifies the ends of the logs and calculates a mean diameter for the logs of the stack. After capturing, the user enters the length of the logs (i.e. stack width), as well as timber assortment (i.e. softwood or hardwood). The application then calculates the stack volume in the cloud service by correcting the gross volume of the stack by an automatic coefficient. The automatic coefficient is determined by the effect of stack width and each detected diameter of logs in the stack. The user can also enter a coefficient manually. The Trestima Stack application calculates and prints to the cloud service the net volume of the stack, the diameter distribution of logs, the total number of logs in the stack, the volume coefficient, the stack length and height, and the geographical information. Spatial information also illustrates the stack orientation, with photographing directions (Trestima Stack, 2018).

There are two pieces of research on the accuracy of measuring energy wood (Luomahaara, 2017) and pulpwood (Pihlajaviita, 2017) stacks with the Trestima Stack application, with quite small datasets. The time consumption (i.e. time per timber measured) in measuring timber stacks using the Trestima Stack application has not been investigated (cf. Luomahaara, 2017; Pihlajaviita, 2017).

Consequently, the aim of the study was to determine the accuracy and time consumption of the Trestima Stack application in timber volume measurement compared to the conventional stacked timber measurement method.

2. Material and methods

2.1. Research data of the study

Research data consisted of a total of 60 timber stacks, of which 32 were measured in large terminal and intermediate yards and 28 at roadside landings (Table 1). The study stacks were located in southern and eastern Finland (Fig. 1). Softwood stacks consisted of mostly (20) Scots pine (*Pinus sylvestris* L.) and (18) Norway spruce (*Picea abies* (L.) Karst.) pulpwood stacks. There were also two contorta pine (*Pinus contorta*) pulpwood stacks in the study. All hardwood stacks were birch (*Betula* spp. L.) pulpwood. The stacks were measured by the Trestima Stack application and the conventional stacked timber measurement method in September 2016 – January 2017.

< Table 1 >
< Fig. 1 >

The control volumes of the stacks were measured in September 2016 – January 2017 at the Stora Enso Anjala, Imatra and Varkaus pulp and paper mills by hydrostatic weighting. The target was to immerse the study stacks as soon as possible following the conventional stacked timber measurement and Trestima Stack measurement. On average, the delay time between the measurement and immersion was 5.4 days and the variation ranged between 0–29 days. The total control volume in the study was 11,957 m^3 solid over the bark (later only: m^3) (Table 1). The stack size at roadside landings was, on average, 72.1 m^3 and varied between 15 and 298 m^3. In terminal yards, the stacks averaged 344.7 m^3 and the variation ranged between 29–1037 m^3.

2.2. Measuring the stack volume with the conventional stacked timber measurement

Each measurement session in the study began with the conventional stacked timber measurement, which mainly followed the official stacked timber measurement instructions in Finland (Kuitupuun pinomittaus, 2003; Luonnonvarakeskuksen määräys, 2017). Stack length was measured with a measurement tape of 20 meters from the edge of the outermost logs at one end of the stack to the edge of the outermost logs at the other end of the stack (Kuitupuun pinomittaus, 2003).

When the stack length was less than 10 meters, the stack height was measured by a Nestle telescope measuring stick with the sections of 1 meter, and when the stack length was 10–20 meters, the stack length was determined with the sections of 2 meters. When measuring stacks in the terminals where they were typically dozens of meters long and the stack height was generally higher than the maximum height in the instructions (i.e. 3 m) (cf. Kuitupuun pinomittaus, 2003), (meaning that stack height measuring with the sections of two meters would have been laborious), the stack height of more than 20 meters long stacks was measured with the sections of 5, 10 or 20 meters, depending on the stack length. Stack height was measured as a perpendicular height from the bottom of the stack to the top of the stack at the centre point of each measuring section. The average stack height was the average value of height measurements taken along the length of the stack. Stack width was taken as the average length of the logs in the stack.

The gross volume of the timber stack was calculated by multiplying the stack length by the stack width and by the average stack height. The solid volume percentage for the stack was determined based on the stack content factors: 1) the mean diameter, 2) branchiness and delimbing, 3) crookedness, and 4) stacking (cf. Kuitupuun pinomittaus, 2003). Stack content factors were estimated independently. When determining them, observations were made on both sides and on the top of the stack. If there were clearly different parts in the stack for estimating the stack content factors, the stack was divided to comply with these differences (cf. Kuitupuun pinomittaus, 2003).

In estimating the mean diameter of logs in the stack, a two-centimetre classification was applied (Table 2). The accuracy of 1 cm was applied in the measurement of log diameters, as well as stack height and width. When measuring the stack length, the accuracy of 1 dm was applied. Diameter was determined by measuring some (over the bark) diameters of the ends of the logs and calculating the arithmetic mean value. Diameters were measured without consideration of whether the log ends were butt or top ends. The log ends measured were selected visually, with the diameters of the log ends representing the mean diameter of all logs in the stack (cf. Kuitupuun pinomittaus, 2003).

< Table 2 >

The branchiness and delimbing class of the logs in the stack was determined by visual estimating and based on the amount of knot stubs and bumps on the surface of the logs in the measuring moment (Table 2). When the crookedness class of the logs in the stack was estimated visually, attention was paid to the natural crookedness of the timber assortment measured. The official stacked timber measurement instructions in Finland (Kuitupuun pinomittaus, 2003; Luonnonvarakeskuksen määräys, 2017) state that the first three crookedness classes (I–III) are applied generally to softwood in the whole of Finland and hardwood from southern Finland. The stacking class of the logs in the stack was also determined by visual estimating (cf. Kuitupuun pinomittaus, 2003) (Table 2).

The solid volume percentage of the stack is determined by calculating the influence values (i.e. correction percentages) of the stack content factors together and by increasing the result to the average solid volume percentage of timber assortment to be measured (Table 3). Finally, the net volume of the stack was calculated by multiplying the gross volume of the stack by the solid volume percentage.

< Table 3 >

2.3. Measuring the stack volume with Trestima Stack

After measuring the volume of the stack by the conventional stacked timber measurement method, the stack was measured with the Trestima Stack application. The application was downloaded to a Samsung Galaxy S6 smartphone. The main camera of the Samsung Galaxy S6 was a 16-megapixel camera with a resolution of 2988 × 5312 pixels. The lens on the Samsung Galaxy S6 was a fixed focal length optic, with a 28 mm-equivalent focal length and a f/1.9 aperture. The Samsung Galaxy S6 was equipped with a 5.10-inch Super Amoled capacitive touchscreen with a resolution of 1440 × 2560 pixels. Thanks to the Corning Gorilla Glass 4, the display of the Samsung Galaxy S6 was damage-resistant, but Samsung Galaxy S6 has not been rated waterproof (Samsung Galaxy, 2018).

With Trestima Stack, a new measurement began by naming the stack. Subsequently, three Trestima Stack reference sticks of one meter long were attached to the stack and an image or several images were taken from the stack (Fig. 2). The number of images depended on the length and height of the stack, as well as the free space available in the storage area. If more than one image had to be taken, one stick could be used to define the starting point of the next image, and thus only two sticks had to be removed. After the photographing, the contours of the stack were limited to the display and the stack width, which was measured during the session of the conventional stacked timber measurement, was added. Timber assortment information (i.e. softwood or hardwood) was also fed into the application.

< Fig. 2 >

After these activities, the image(s) moved to a cloud service, where the application determined the solid percentage volume by correcting its internal formulas using the stack width and the estimated diameters of logs. The net volume of the stack was finally obtained by multiplying a corrected solid percentage volume by the gross volume of the stack. The application indicated when the net volume of the full stack had been counted and checked. The final image frame was bounded by the machine vision algorithms of the Trestima Stack system and checked by Trestima company's staff before the application reported the 100% ready results (Fig. 2).

2.4. Other measurements and evaluations

After the measuring session of the stack volume by Trestima Stack, the distances between the stack and photographing places were measured. In addition, following the measurement activities, the control mean diameter (over the bark) of the logs in the stack was measured by a Haglöf caliper, by measuring all ends of logs from inside of a square plot area of 1×1 meter. When the stack length was less than 10 meters, there was one square. When the stack was 10–20 meters long and more than 20 meters long, two and three squares were used, respectively. The measured control mean diameter of logs and the standard deviation of the diameter of logs were calculated for all stacks.

In addition, for all stacks the air temperature (^{o}C) during measuring the stacks with the conventional stacked timber measurement method and Trestima Stack after the measurement sessions were recorded. The air temperature varied between +7^{o}C and –11^{o}C during the measurement sessions. Moreover, the depth of snow cover on the top of each stack was measured in the study. The snow covered the ground and the stack in every fourth stack measurement. When there was snow, the depth of snow cover ranged from 1–36 cm on the top of the stack.

In addition, the following factors for each stack were evaluated and five dummy variables were built:

- Successful final Trestima image framing around the stack measured: 1=Yes, it was; 0=No, it was not (i.e. a lot of empty space or too tight framing) (Fig. 3).
- Visual obstacles in the Trestima image: 1=Yes, there were some obstacles (e.g. tree branches, snow cover) (Fig. 4); 0=No, there were no obstacles in the image (Fig. 2).
- Stack was covered by snow: 1=Yes (Fig. 4); 0=No, there was no snow cover on the top of the stack.
- Flat stack bottom: 1=Yes, it was (i.e. flat storage field and/or skid logs under the stack (Fig. 2); 0=No, it was not (e.g. rocks and stumps under the stack or the stack being located on the slope) (Fig. 3).
- Only one timber assortment in the stack: 1=Yes; 0=No, there were more than one timber assortments in the stack.

< Fig. 3 >

< Fig. 4 >

2.5. Reference measurement of the stack volume in immersion

Once all measurements had been completed, the stack was marked with spray and labels for the drivers of timber trucks or the operators of log stackers depending on the stack location. The stacks measured at roadside landings or in intermediate storage were transported by either truck or train to the mill, where log stackers used (Anjala: Kalmar RTD3126, Imatra: Mantsinen LH32 and Varkaus: Kalmar RTD3026 and TW LogStacker RTD3126) (Mantsinen, 2018; TW, 2018) immersed pulpwood bundles into the measuring containers and the operators of log stackers saved the measurement results.

In the hydrostatic weighting based on the immersion measurement, a log stacker weighted the pulpwood bundle first in air and subsequently in water. The volume of the pulpwood bundle could be calculated by subtracting the latter value from the former using the formula of hydrostatic weighting (Sipi, 2009) (Eq. 1):

$$V_i = (m_a - m_w) / (\rho / 1000) \quad (1)$$

where V_i = the volume of the bundle in immersion (m^3), m_a = bundle mass in air (kg), m_w = bundle mass in water (kg) and ρ = water density (kg/m^3).

The accuracy – i.e. the measurement difference – of the measurement methods used was obtained by subtracting the volume of the immersion measurement from the volume obtained by the measurement method used (Eq. 2):

$$D = ((V_m - V_i) / V_i) \times 100 \quad (2)$$

where D = the measurement difference (%), V_m = the volume of the stack by the Trestima Stack measurement / the volume of the stack by the conventional stacked timber measurement (m^3) and V_i = the volume of the stack in the immersion (m^3).

2.6. Time consumption study

To clarify the effective (E_0) hour time consumption with the measurement methods used, the duration of time consumption elements in each measuring session was timed. The accuracy was one second (s). The main time consumption elements in the study were:

1) Measurement of stack length and height, and estimating stack content factors,

2) Measurement of stack width, and
3) Calculation of results.

Delays of measurement sessions were not considered in the study. The measurement time of stack length and height, and estimating stack content factors, began when a research scientist started to move with the measurement tools from a car which had been parked near the stack towards the stack, and ended when the measuring of the stack length and height and estimation of the stack content factors had been completed, and the research scientist had returned to the car.

With the conventional stacked timber measurement method, the time consumption of the calculation of measurement results began when the research scientist started to calculate the results with a calculator, and ended when the results were ready. On the other hand, with the Trestima Stack application, the time consumption of the calculation of the results began when the images uploaded to the cloud service, and ended when the application informed the researcher that the results were ready. When the time element of the calculation of the results with Trestima Stack took more than 30 minutes, the timing was interrupted, and subsequently that kind of stack (n=7) did not acquire the time consumption of the calculation of the measurement results, as well as the total effective time consumption (i.e. seconds per stack).

The time to measuring the stack width was timed separately when measuring the stack with the conventional stacked timber measurement method, and was added to the total effective time consumption for both of the measurement methods used. The timber volume-based effective total time consumption for each stack was calculated by dividing the total effective time consumption by the timber volume measured (Eq. 3):

$$T_v = T_T / V_i \qquad (3)$$

where T_v = timber volume-based effective total measurement time consumption (s/m^3), T_T = total effective measurement time consumption (s) and V_i = the volume of the stack in the immersion (m^3).

2.7. Data analysis

The Decree set by the Ministry of Agriculture and Forestry in Finland specifies the accuracy requirements for the measurement of timber volume. When measuring timber at the roadside landing, the maximum allowable deviation in measurement results is 14%, with a stack size of 10–30 m^3. When the size of stack is 30–60 m^3, 60–150 m^3 and >150 m^3, the maximum deviation in the measurement results is 10%, 7% and 4%, respectively (Maa- ja metsätalousministeriö, 2013).

Based on the Decree set by the Ministry of Agriculture and Forestry, the measurement differences of the stacks produced by the measurement methods used were classified into two groups:

1) the fulfilled (measurement difference is inside of the maximum allowable deviation) and

2) not fulfilled (measurement difference is outside of the maximum allowable deviation) measured stacks.

In contrast, the stacks associated with the effective total time consumption (seconds per m^3 of timber) with the Trestima Stack and the conventional stacked timber measurement methods were categorized into three groups:

- Trestima Stack: Group A: <4 s/m^3, B: 4–13 s/m^3 and C: >13 s/m^3 and
- Conventional timber measurement: Group A: <6 s/m^3, B: 6–17 s/m^3 and C: >17 s/m^3.

The variables related to measurement accuracy and time consumption in the study were analysed using percentage shares and distributions, mean values, standard deviations and Spearman's rank correlations (ρ). The statistically significant differences between the classified groups of measurement accuracy and effective total time consumption were researched using the Mann-Whitney test (U) and the Kruskal-Wallis one-way ANOVA test (χ^2), because the circumstances (i.e. ratio or interval scales in variables and/or normal distribution of samples) for using parametric tests did not exist. All statistical analyses in the study were conducted with IBM SPSS Statistics 21 software (IBM SPSS, 2018).

3. Results

3.1. Accuracy of the measurement methods

Across all the study data, on average, the measurement accuracy (i.e. measurement difference) of Trestima Stack was statistically significant better (+2.7%) than that of the conventional stacked timber measurement method (–4.9%) (U=1064.0; *p*<0.001) (Table 4). In large terminal yards, the measurement accuracy of Trestima Stack averaged better (+0.6%) than at roadside landings (+4.5%). However, when standard deviations were high (Table 4), there was no statistically significant difference between stack locations (terminal vs. roadside landing) in the Trestima Stack measurements (U=330.0; *p*=0.080).

< Table 4 >

When measuring with the conventional stacked timber measurement method, the measurement accuracy was almost at the same level in terminal yards (–4.8%) and at roadside landings (–4.9%), and there was no statistically significant difference between the stack locations in the conventional stacked timber measurements (U=428.0; p=0.927).

The absolute mean of Trestima Stack was, on average, 8.8% and 8.3% with the conventional stacked timber measurement method. There was no statistically significant difference between the measurement methods used in the absolute means (U=1792.0; p=0.907) (Table 4).

Typically, Trestima Stack produced too high volumes for the stacks and the conventional stacked timber measurement method gave too small volumes compared to the control stack volumes by the immersion measurement (Table 4, Fig. 5). The measurement differences were the largest with small (<150–200 m^3) timber stacks with both the conventional stacked timber measurement method and Trestima Stack. For both measurement methods, there were no statistically significant correlations between the size of stack volume and the average measurement difference (Trestima Stack: ρ= –0.238; p=0.067 and conventional timber measurement: ρ= –0.073; p=0.581) (Fig. 5). Nonetheless, there was a statistically significant negative correlation between the size of stack volume and the absolute mean of measurement difference with Trestima Stack (ρ= –0.267; $p<0.05$) but not with the conventional stacked timber measurement method (ρ= –0.120; p=0.367).

< Fig. 5 >

In the study, the average measurement accuracy of Trestima Stack satisfied the accuracy limits set by the Ministry of Agriculture and Forestry in Finland (Maa- ja metsätalousministeriö, 2013) in all measuring categories (Table 5). In contrast, with the conventional stacked timber measurement method, the average measurement accuracy did not satisfy the accuracy requirements determined in the category of the measurement batches of more than 150 m^3 (Table 5).

< Table 5 >

When detecting the groups of the fulfilled and not fulfilled timber stacks measured according to the Decree (Maa- ja metsätalousministeriö, 2013) with the measurement methods used, there was only one statistically significant difference between the fulfilled and not fulfilled stacks (Tables 6 and 7). With the fulfilled or satisfactory Trestima Stack measurements, the final Trestima image framing around the stack measured was significantly successful (Table 6). Furthermore, the results indicated that the fulfilled stacks were located more frequently in terminals than not fulfilled stacks, as well as the fact that these stacks were not covered by snow. The bottoms of these stacks were also frequently flat. Nevertheless, the differences in these variables between the fulfilled and not fulfilled stacks were not statistically significant.

< Table 6 >
< Table 7 >

With the fulfilled or satisfactory stacks measured by the conventional stacked timber measurement method, there was only a thin snow cover on the top of the stacks (Table 7). The results also illustrated that the fulfilled stacks were smaller and lower, as well as the bottom of these stacks being frequently uneven. However, there were no statistically significant differences between these stack characteristics.

3.2. Time consumption of the measurement methods

The average effective total measurement time consumption with Trestima Stack was lower (10.6 s/m^3) than that of the conventional stacked timber measurement method (13.7 s/m^3) but there was no statistically significant difference between measurement methods used in the effective time consumption per timber measured (U=1826.0; p=0.059). For both measurement methods used, measuring the stacks at roadside landings took, on average, more time than doing so in terminals (Fig. 6).

< Fig. 6 >

With the conventional stacked timber measurement method, the measurement of stack length and height and estimating the stack content factors took the main part of the total effective time consumption (Fig. 6). With Trestima Stack, these measurement activities took, on average, only 43% of the total effective time consumption. Correspondingly, the calculation of measurement results averaged 10% of the total effective time consumption with the conventional stacked timber measurement method and even 38% of the total effective time consumption with Trestima Stack. The share of the measurement of stack width was, on average, 20% of the total effective time consumption with Trestima Stack and 15% with the conventional stacked timber measurement method (Fig. 6).

For both the measurement methods used, there were statistically significant negative correlations between the size of stack volume and effective total measurement time consumption per timber measured (Trestima Stack: ρ= –0.853; p<0.001 and conventional timber measurement: ρ= –0.854; p<0.001) (Fig. 7).

< Fig. 7 >

When investigating the timber volume-based effective total measurement time consumption with Trestima Stack, the stacks which had a small effective total measurement time consumption (<4 s/m^3) were, significantly, large, long and high terminal stacks from which several images had been taken and where the photographing distances between the stack and measuring places were fairly long (Table 8). Furthermore, the classification that was created indicated that the fast-measured (<4 s/m^3) stacks were more commonly the stacks where visual obstacles in the image were infrequent, snow did not cover the stack, and the stack bottom was flat. Nonetheless, these variables did not show statistically significant difference between the groups (Table 8).

< Table 8 >

Of further significance, the fast-measured (effective total measurement time consumption <6 s/m^3) stacks by the conventional stacked timber measurement method were big, long and high terminal stacks (Table 9). Moreover, these fast-measured stacks with the conventional stacked timber measurement method consisted of smaller-diameter timber, and the bottom of these kind of stacks was even (Table 9).

< Table 9 >

4. Discussion

4.1. Study material and its reliability

The study material totalled more than 11,000 m^3, including 60 stacks measured. The amount of material was quite extensive compared to the earlier Trestima Stack researches. The material in the research by Luomahaara (2017) was 503 m^3, with 20 stacks measured and in the research by Pihlajaviita (2017) it was 600 m^3 with 34 stacks. In this study, the stack volumes ranged from 15–

1037 m^3, and the average stack volume at roadside landings was 72 m^3 while in terminals it was 345 m^3. Hence, the size of the stacks measured in the study was significantly larger than those of Luomahaara (2017) and Pihlajaviita (2017). In the research by Luomahaara (2017) the stacks varied between 2 and 65 m^3, and between 2 and 53 m^3 in the research by Pihlajaviita (2017). Correspondingly, in the study by Jodłowski et al. (2016), in total 539 log piles with the volume of 39,372 m^3 of stacked wood were measured with the Fovea and AFoRS photo-optical systems. In the research by Mederski et al. (2018), in total 39.6 m^3 of timber with three stacks was measured with a sScale application. Even though the study material consisted of 60 stacks measured, the number of stacks was not particularly large since there were lots of independent variables in the study which impacted on the measurement accuracy and time consumption (cf. Tables 6–9).

When collecting the accuracy data of measurement methods, a close collaboration between the many actors in the whole measurement chain is called for. Following measurements with the conventional stacked timber measurement method and Trestima Stack in the study, the pulpwood logs of the stacks had to be transported to the mill and immersed there. The measurement chain had to be monitored and clear communication ensured so that the right logs were transported to the mill and immersed into the measuring container, and the control measurement results obtained. Mistakes could arise anywhere in the measurement chain.

In the study, each measurement result for all timber stacks was carefully analysed. In particular, if there was a significant gap between the measurement results from the Trestima Stack measurement and the conventional stacked timber measurement, and on the other hand with the control measurements of the immersion, there was an attempt to discover the reasons for the variation. Nevertheless, the logical and obvious reasons for the measurement differences observed failed to be revealed. Therefore, any measured timber stacks were deleted from the final study data. As Fig. 5 illustrates, there were some quite big (>±20%) measurement differences in the study.

The pulpwood bundles at the mill were weighted by the log stackers' crane scales based on the strain gauge or hydraulic pressure measurement in the study. Hokka and Vuorenpää (2001) researched the reliability and accuracy of crane scales in the wood handling machines at the pulp and paper mills and concluded that they work reliably and accurately when they have been properly calibrated, and the operator of a log stacker is careful and follows systematically the measurement results of the crane scale to the reference scale or scales used.

4.2. Accuracy of measurement methods used

There are two earlier pieces of research on the accuracy of measuring timber stacks with the Trestima Stack application (Luomahaara, 2017; Pihlajaviita, 2017). In the research by Luomahaara (2017), the measurement accuracy of Trestima Stack was weaker than that of the conventional stacked timber measurement: Trestima Stack had an average difference of +5.1% and the conventional stacked timber measurement had an average difference of +1.6%. In contrast, Pihlajaviita (2017) revealed that the measurement accuracy with Trestima Stack and the conventional stacked timber measurement method averaged at the same level: The average measurement difference of Trestima Stack was +2.3% with softwood and –2.4% with hardwood. On average, the conventional stacked timber measurement method produced the measurement difference of +1.7% with softwood and –2.6% with hardwood.

In research by Mederski et al. (2018), the measurement accuracy varied between –1.8% and +1.8% when measuring windthrown timber with the sScale application. Furthermore, the Forest Journal magazine (Made to Measure, 2015) reported a measurement accuracy of ±2% with the sScale application compared to a reference measurement at the mill. In the study by Jodłowski et al. (2016), the measurement accuracy of the Fovea and AFoRS photo-optical systems was clarified, and their measurement results were compared to the conventional stacked timber measurement method. The obtained measurement difference averaged +0.8% for the AFoRS and +1.0% for the Fovea compared to the conventional measurement method (Jodłowski et al. 2016).

Several studies have introduced new machine vision-based applications for estimating the volume of log stacks. They reported the following accuracies: Herbon et al. (2015) presented a novel method for photogrammetric wood pile surveying (i.e. 3D reconstruction technique) and found an average absolute difference of 5.6% with the solid volume of the stack. On the other hand, Kruglov et al. (2017a; 2017b) and Kruglov (2018) developed a mobile measurement for roundwood based on a timber volume measurement algorithm. Their validation tests indicated that the average error for the log pile photogrammetry measurement is 5.1% with a maximum error of 9.2% in comparison to manual measurement. Correspondingly, Mehrentsev and Kruglov (2017) developed the algorithm and software for timber batch volume measurement using image analysis and reported that the error of the software compared to manual piece-by-piece measurement is less than 7.1%, with an average error of 4.9%.

In this study, the measurement accuracy of the Trestima Stack application was significantly better than that of the conventional stacked timber measurement method: The average measurement difference was +2.7% with Trestima Stack and –4.9% with the conventional stacked timber measurement method. Thus, the measuring accuracy of the Trestima Stack application in the study was at the same level as the measurement research results by Pihlajaviita (2017) and Mederski et al. (2018), and at a significantly lower level to the results by Jodłowski et al. (2016).

One interesting observation in this study is the fact that, on average, the Trestima Stack measurement gave frequently too high stack volumes (i.e. positive measurement differences) compared to the control measurement by the immersion. Correspondingly, the conventional stacked timber measurement method produced frequently too small volumes (i.e. negative measurement differences) for the stacks when compared with the control measurement. In successful storage management, a small negative difference is a better situation than a positive difference in terms of the wood supply of mills. That is, when the storages have a little more timber, the planned deliveries will be more secure. However, when the measurement results indicate higher timber volumes than those of the actual storages, problems in the wood supply occur when the timber volumes for the planned deliveries are not found in the storages.

Moreover, the results revealed that the average measurement results with the Trestima Stack application fulfilled in all timber volume classes of measurement batches according to the accuracy requirements set by the Ministry of Agriculture and Forestry in Finland (Maa- ja metsätalousministeriö, 2013). Instead, with the conventional stacked timber measurement method, when measuring the timber measurement batches of more than 150 m^3, the average measurement difference was not inside the limits of maximum allowable deviation (±4%) (cf. Table 5).

In the study with the conventional stacked timber measurement method, the stack size did not have statistically significant effect on the measurement accuracy, neither the average measurement difference nor the absolute mean of measurement. This result is not in line with, for instance, the memo for the Ministry of Agriculture and Forestry in Finland written by Lindblad and Verkasalo (2005) who disclosed that the size of stack affects significantly the measurement accuracy and displayed that when the volume of timber stack measured decreases less than 150 m^3, there are big challenges to achieve the measurement accuracy of ±4% with the conventional stacked timber measurement method. On the contrary, there was a clear negative connection between the stack volume and the measurement accuracy with the Trestima Stack measurements in the study: the larger the measured stacks, the lower the average measurement differences and absolute means (cf. Table 5, Fig. 5).

The results illustrate that the most significant variable which profiles the groups of fulfilled and not fulfilled measurements with the Trestima Stack application was the successful final image framing around the stack (cf. Table 6). Mostly, the empty space was in the bottom of the stack in the image. It can be estimated that the empty space around the stack in the Trestima Stack image was probably the reason for the significant positive measurement difference in the Trestima Stack measurements.

The other reason for the frequently positive measurement difference with Trestima Stack might be the fact that the Trestima Stack application did not identify all ends of pulpwood logs from the stack in the image. In many cases, these unidentified logs were smaller-diameter logs (cf. Figs 2 and 3). It produced, on average, a 3.6 cm higher mean diameter estimate for the pulpwood logs of the stack than the control measurement, based on the square measurements reported in the study (Table 6). Subsequently, it gave, on average, an error of 2–4% for the correction percentage of the mean diameter of logs in the stack when estimating the stack content factors (cf. Table 2), a further too high average solid volume percentage for the stack (cf. Table 3), and finally too big stack volume when calculating the net stack volume.

4.3. Time consumption in the measurement of stacks

The study produced new information about the time consumption of the utilization of the Trestima Stack application (cf. Luomahaara, 2017; Pihlajaviita, 2017). For both measurement methods used, the effective total time consumption per timber measured (s/m^3) was the lowest when, on average, the stack volume was the largest. In the study, Trestima Stack averaged a faster measurement method than the conventional stacked timber measurement method. With the Trestima Stack application, the calculation of measurement results took almost the same time as the actual Trestima Stack measurement, i.e. measuring the stack length and height and estimating the stack content factors. Furthermore, Jodłowski et al. (2016) reported that the time consumption of timber measurement with two photo-optical measurement applications (AFoRS and Fovea) is lower than measuring log piles using the conventional stacked timber measurement method. In research by Jodłowski et al. (2016), the total measurement time was, on average, 11.4 s/m^3 with the conventional stacked timber measurement and 5.4 and 7.2 s/m^3 with the AFoRS and Fovea applications, respectively.

The time element of the calculation of measurement results depended on the staff of Trestima company, because they checked all Trestima Stack images taken. During the study time, the Trestima Stack application was not widely in use. Subsequently, when the number of Trestima Stack users increase, the processing times of Trestima Stack images will also accelerate when Trestima company allocates more resources for image checking, or fully automatizes the image processing so that there is no need to check the images taken by humans. On the other hand, the time consumption of the calculation of measurement results can be considered a less critical factor for the utilization of the Trestima Stack, because the Trestima Stack user can carry out other activities during the calculation of the Trestima Stack results.

In the study, the cubic meter-based effective measurement time consumption in the Trestima Stack measurements was in particular the lowest for the large terminal stacks where several images were taken and where the photographing distances were relative long. In addition, some other variables (e.g. no visual obstacles in the image, uncovered stacks by snow, flat storage field and/or skid logs under the stack) illustrated the low measurement time consumption with the Trestima Stack application but did not statistically categorize the groups in the study.

In the conventional stacked timber measurement, the measurement of stack length and height and the estimation of the stack content factors took most of the time. The handling of measuring instruments took considerable time, as well as the visual evaluation of the stack content factors. In particular, it is challenging to measure accurately the stack heights when they are high and the top of the stack is not even (cf. Heiskanen, 1973a). Correspondingly, the calculation of measurement results was quickly performed with a calculator. In fact, the calculation of measurement results with the conventional stacked timber measurement method averaged about four times faster than that of the Trestima Stack application.

As with the Trestima Stack application, the conventional stacked timber measurement method was fast for measuring large, long and high terminal stacks which frequently had flat stack bottoms. It was challenging to accurately determine the dimensions of the stacks which had been stacked over the big rocks and stumps or to slope with the conventional stacked timber measurement method. In addition, for both measurement methods used, snow cover slowed down the measuring of the study stacks.

5. Conclusions

In the study, the machine vision-based mobile Trestima Stack application was a more accurate and faster measuring tool than the conventional stacked timber measurement method. In particular, the velocity of the Trestima Stack application was observed when the stacks, which included several measurement batches, were measured. Trestima Stack was also a handy measuring tool. That is, it was downloaded to a smartphone, which is easily stored in the pocket of a measurer.

The main weaknesses of the Trestima Stack application in the study were 1) the determining of the gross volume of the stack and 2) the considerable length of waiting time of measurement results. Namely, during the time of data collection (i.e. in the late of 2016 and at the beginning of 2017), the Trestima image framing around the stack could not be modified afterwards in the internet service of the application. When the Trestima Stack application becomes more common, it is forecasted that the calculation of measurement results from Trestima company staff checking the final image framing will be done faster. Moreover, the recognition of a ready measurement result (i.e. Checked 100%) could be improved by giving a beep signal or changing from a red to green colour when 100% ready as a checking mark. In the data gathering of the time consumption in the study, waiting for the measurement results to be completed was difficult due to the shutdown and locking of the phone display. The automatization of the calculation of measurement results could enhance the utilization of the Trestima Stack application. In addition, the functionality of the application in rainy and freezing weather must still be tested in the future. In the study, the conditions of small rainfalls and some minus degrees in the air temperature did not cause any problems for the use of the application.

Although Trestima Stack is very accurate, especially when measuring large quantities in terminal and intermediate yards, the use of Trestima Stack in narrow gaps between timber stacks is not easy. In terminals, timber stacks are normally stored side by side due to the lack of space. These timber yards are currently measured by multiplying the volume of the first stack by the number of stacks behind it, because it is impossible to measure the middle stacks. Trestima Stack will not remove the challenges of volume estimation in such timber yards. Therefore, this study recommends the Trestima Stack application for inventorying timber stacks at roadside landings, particularly when the stacks measured consist of several measurement batches.

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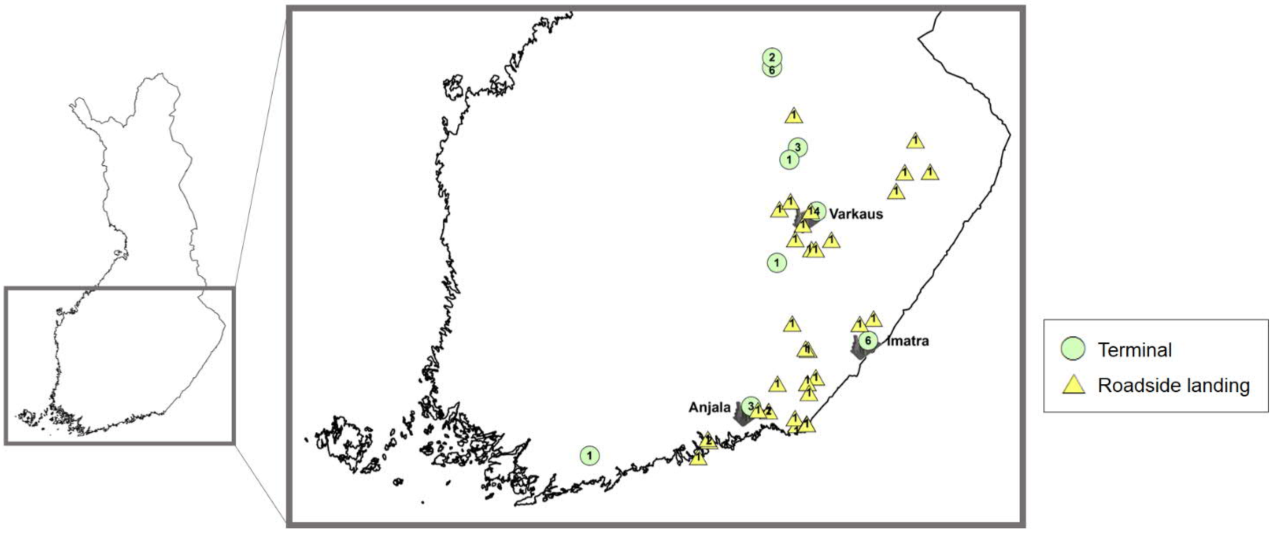


Fig. 1. Geographical distribution of stacks measured in terminals and at roadside landings in the study. The number of the stacks measured in a certain location has been marked with numbers (1…6). The control measurements of stacks were conducted at the Stora Enso Anjala, Imatra and Varkaus mills.

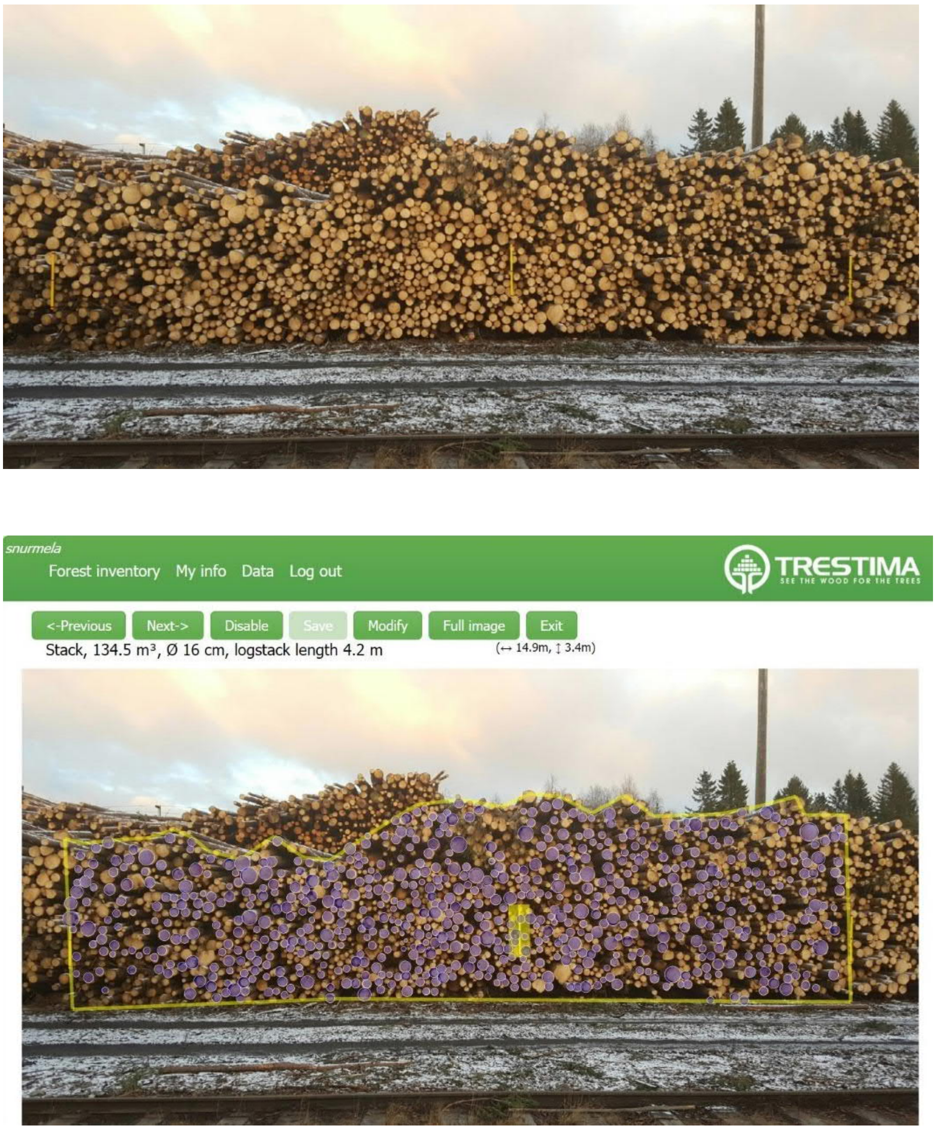
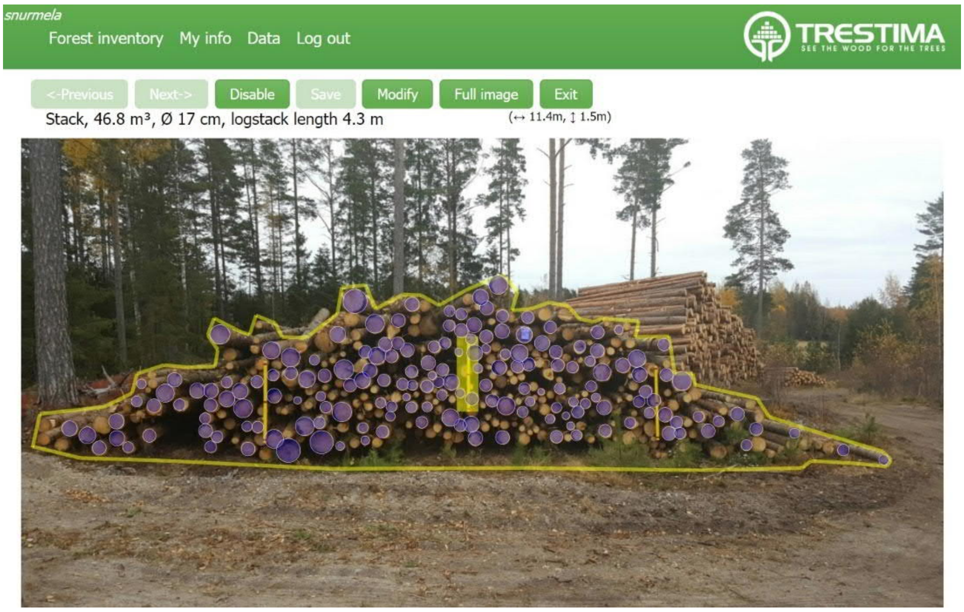


Fig. 2. Trestima Stack measurement has been started and three yellow reference sticks of one meter long have been attached to a stack (top). One image from the stack measured has been taken and analysed with the final frame bounded, as well as being checked by Trestima company staff (down).



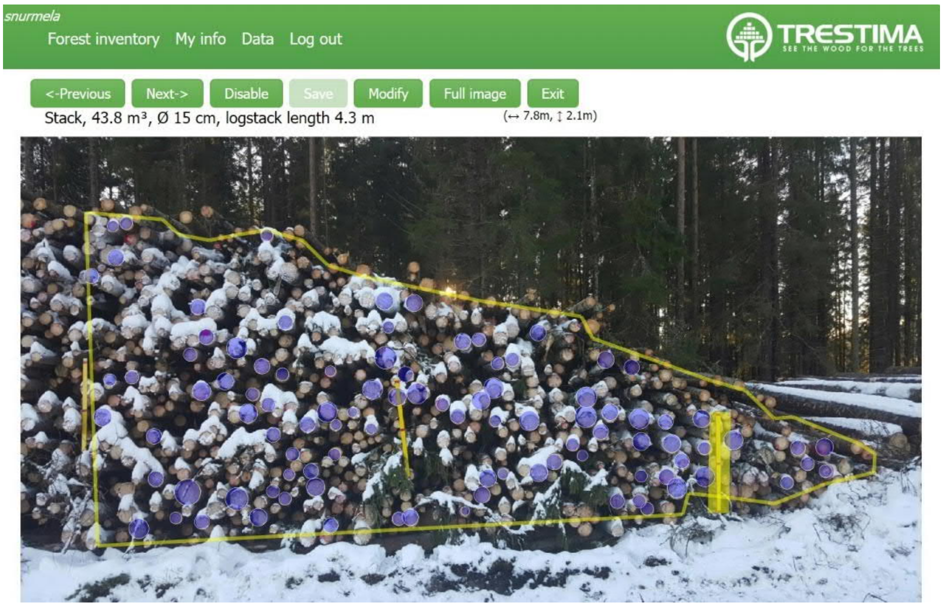


Fig. 3. A lot of empty space in the final Trestima image framing around the stack (top) and too tight image framing which leaves logs outside of an image analysis (down).

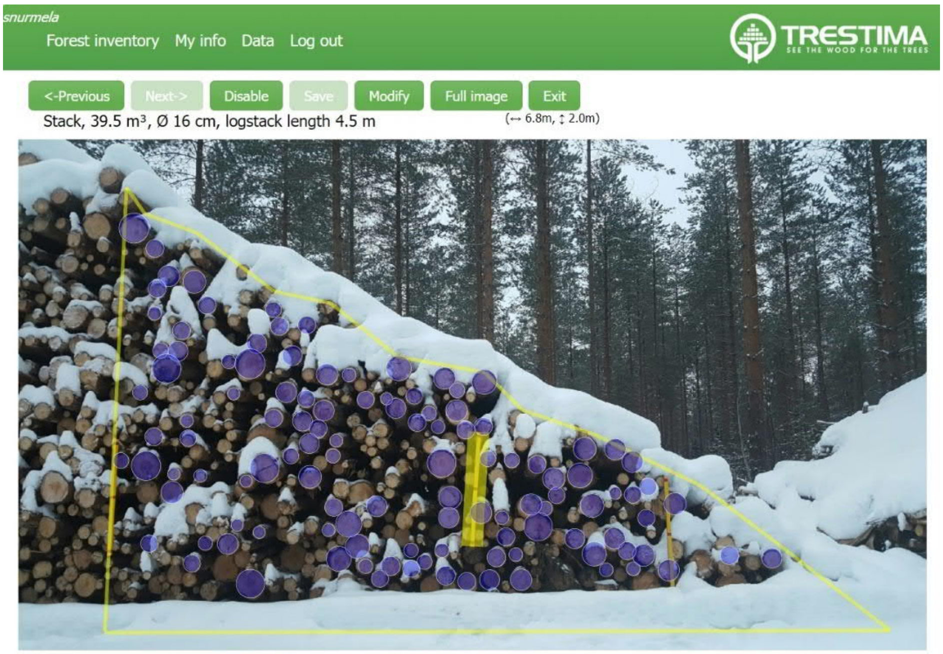


Fig. 4. Visual obstacles (e.g. snow cover, tree branches) in the Trestima Stack image cause challenges for the image framing. In this image, a Trestima Stack measurer has estimated that the bottom of stack is under snow cover.

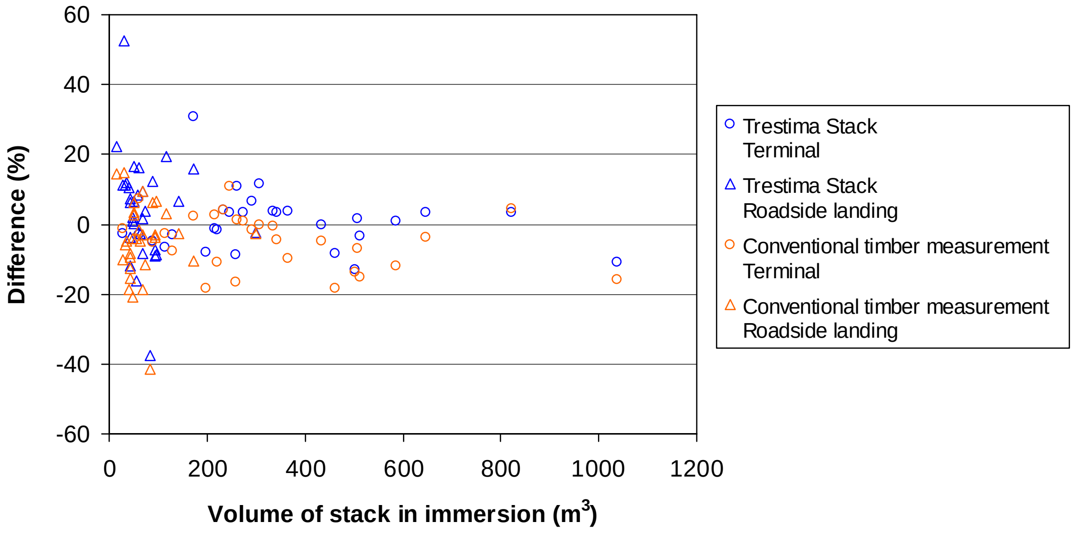


Fig. 5. Measurement differences as a function of the volume of stack in the immersion measurement with the measurement methods used in terminals and at roadside landings.

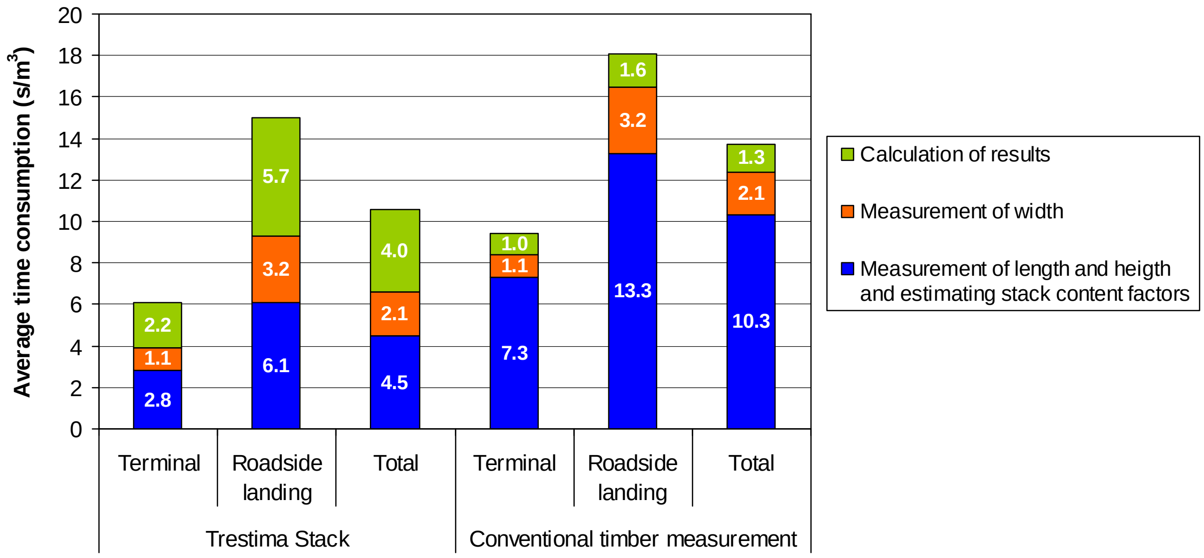


Fig. 6. Distribution of the average effective time consumption by the main time element and stack location with the measurement methods used in the study.

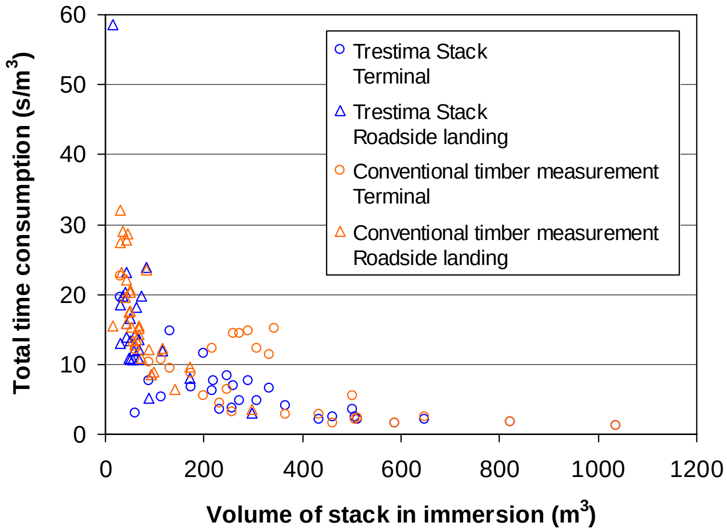


Fig. 7. Effective total measurement time consumption as a function of the volume of stack in the immersion measurement with the measurement methods used in terminals and at roadside landings. The effective total measurement time consumption for seven stacks with Trestima Stack was not determined because the calculation of the measurement results of these stacks took more than 30 minutes.

Table 1

The number and volume of the stacks measured by stack location and main timber assortment in a stack. The volumes are the control volumes produced by an immersion measurement at the mill.

Stack location Main timber assortment in stack	Number of stacks	Volume of stacks (m^3)
Terminal	28	9651
Softwood	19	7621
Hardwood	9	2030
Roadside landing	32	2306
Softwood	21	1706
Hardwood	11	600
Total	60	11,957

Table 2

Stack content factors and their influence (i.e. correction percentages) on a solid volume percentage with softwood and hardwood (Kuitupuun pinomittaus, 2003). The verbal description of a class is in parentheses under each class.

Stack content factor Class Description of class	Softwood	Hardwood
	Correction percentage (%)	
Mean diameter class (cm)		
9	–3	–3
11	0	0
13	+2	+2
15	+3	+4
17	+4	+6
19	+4	+7
21	+5	+8
23	+5	+8
>23	+6	+9
Branchiness and delimbing class		
I	+2	+1
(No knot stubs neither knot bumps)		
II	0	0
(Some short knot stubs and small knot bumps)		
III	–2	–1
(Knot stubs and knot bumps occasionally)		
IV	–4	–2
(Plenty of knot stubs and knot bumps)		
Crookedness class		
I	+1	+2
(Logs are straight)		
II	0	0
(Logs represent the average natural crookedness of timber assortment)		
III	–1	–2
(Logs are crooked. Crookedness of logs causes holes in a stack)		
IV †	–2	–4
(Logs are mostly very crooked)		
V ‡	..	–6
(Virtually all logs are very crooked)		
Stacking class		
I	+2	+1
(Logs are tightly interlocked)		
II	0	0
(Logs are somewhat crossed. Stacking causes gaps between logs)		
III	–2	–1
(Many logs are crossed. There are large gaps due to stacking)		
IV	–4	–3
(Logs are very abundantly crossed. There are large gaps due to stacking)		

† It can only occur in hardwood, especially in northern Finland.

‡ It can only occur exceptionally in hardwood in northern Finland.

.. It has not been determined.

Table 3

The average solid volume percentages by the length class of timber in the stack with softwood and hardwood (Kuitupuun pinomittaus, 2003).

Length class of timber in stack (m)	Softwood	Hardwood
	Average solid volume percentage (%)	
2.00 – 2.50	66	57
2.51 – 3.50	63	54
3.51 – 4.50	61	52
4.51 – 5.50	60	50
5.51 – 6.00	59	49

Table 4

The average measurement differences, standard deviations and absolute means with the Trestima Stack application and the conventional stacked timber measurement method by stack location and main timber assortment in the stack.

Stack location Main timber assortment in stack	Trestima Stack			Conventional timber measurement		
	Average difference (%)	Standard deviation (%)	Absolute mean (%)	Average difference (%)	Standard deviation (%)	Absolute mean (%)
Terminal	+0.57	8.47	5.94	–4.84	7.98	7.23
Softwood	+0.54	6.55	5.11	–5.99	6.76	6.92
Hardwood	+0.63	12.08	7.70	–2.40	10.11	7.89
Roadside landing	+4.51	14.92	11.26	–4.88	11.32	9.21
Softwood	+4.32	17.73	12.98	–3.64	12.29	9.17
Hardwood	+4.86	7.83	7.97	–7.50	8.95	9.30
Total	+2.67	12.40	8.78	–4.86	9.79	8.27

Table 5

Maximum allowable deviation in a measurement result by the volume class of measurement batch according to the Decree set by the Ministry of Agriculture and Forestry in Finland (Maa- ja metsätalousministeriö, 2013), the distribution of the stacks measured by the volume class in the study and the average measurement differences and absolute means with the Trestima Stack application and the conventional stacked timber measurement method.

Volume class of measurement batch (m^3)	Maximum allowable deviation (±%)	Number of stacks in study	Trestima Stack	Conventional timber measurement	Trestima Stack	Conventional timber measurement
			Average difference (%)		Absolute mean (%)	
10–30	14	3	+10.23	+1.09	12.07	8.59
30–60	10	16	+6.21	–4.67	10.55	9.27
60–150	7	16	–1.20	–5.04	9.83	8.21
>150	4	25	+1.98	–5.57	6.57	6.57

Table 6

Description of fulfilled and not fulfilled measured stacks categorized according to the Decree set by the Ministry of Agriculture and Forestry in Finland (cf. Table 5) and statistically significant differences between the stack groups when measuring with the Trestima Stack application.

	Average (n=60)	Fulfilled stacks (n=35)	Not fulfilled stacks (n=25)	Stat. significant difference between the groups
Stack location (%)				
Terminal	47	54	36	
Roadside landing	53	46	64	
Main timber assortment in stack (%)				
Softwood	67	63	72	
Hardwood	33	37	28	
Stack length (m)	30.4	32.3	27.8	
Stack height (m)	2.20	2.19	2.20	
Ratio of length and height of stack	14.3	15.2	13.1	
Stack width (m)	4.08	4.08	4.08	
Mean diameter of logs estimated by Trestima (cm)	17.2	17.1	17.3	
Number of logs in stack	2009	2073	1919	
Solid volume percentage (%)	63.0	62.7	63.3	
Volume of stack estimated by Trestima (m^3)	199.8	213.2	181.1	
Number of measurement batches	1.6	1.5	1.6	
Volume of stack in immersion (m^3)	199.3	210.1	184.1	
Measured control mean diameter of logs (cm)	13.6	13.3	14.0	
Standard deviation of diameter of logs (cm)	5.2	5.0	5.4	
Air temperature (°C)	+0.0	–0.1	+0.2	
When snow, depth of snow cover (cm)	10.2	7.5	12.5	
Number of Trestima images per stack	3.8	3.9	3.5	
Photographing distance (m)	6.6	6.9	6.3	
Successful final Trestima image framing (%)				
Yes	50	63	32	*
No	50	37	68	
Visual obstacle in Trestima image (%)				
Yes	28	37	16	
No	72	63	84	
Stack covered by snow (%)				
Yes	25	20	32	
No	75	80	68	
Flat stack bottom (%)				
Yes	38	46	28	
No	62	54	72	
Only one timber assortment in stack (%)				
Yes	93	94	92	
No	7	6	8	

* $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Table 7

Description of fulfilled and not fulfilled measured stacks categorized according to the Decree set by the Ministry of Agriculture and Forestry in Finland (cf. Table 5) and statistically significant differences between the stack groups when measuring with the conventional stacked timber measurement method.

	Average (n=60)	Fulfilled stacks (n=35)	Not fulfilled stacks (n=24)	Stat. significant difference between the groups
Stack location (%)				
Terminal	47	43	54	
Roadside landing	53	57	46	
Main timber assortment in stack (%)				
Softwood	67	66	71	
Hardwood	33	34	29	
Stack length (m)	26.4	25.8	27.2	
Stack height (m)	2.54	2.30	2.89	
Ratio of length and height of stack	11.4	12.4	9.8	
Stack width (m)	4.08	4.17	3.99	
Estimated mean diameter of logs (cm)	16.2	16.3	16.1	
Branchiness and delimbing class (%)				
I	0	0	0	
II	98	97	100	
III	0	0	0	
VI	2	3	0	
Crookedness class (%)				
I	0	0	0	
II	98	100	95	
III	2	0	5	
Stacking class (%)				
I	0	0	0	
II	100	100	100	
III	0	0	0	
Solid volume percentage (%)	62.1	61.7	62.5	
Volume of stack estimated by conventional timber measurement (m^3)	189.1	164.0	225.7	
Number of measurement batches	1.6	1.8	1.2	
Volume of stack in immersion (m^3)	199.3	164.4	256.1	
Measured control mean diameter of logs (cm)	13.6	13.5	13.7	
Standard deviation of diameter of logs (cm)	5.2	4.8	5.8	
Air temperature (°C)	+0.0	–0.1	+0.2	
When snow, depth of snow cover (cm)	10.2	4.2	22.2	*
Stack covered by snow (%)				
Yes	25	29	21	
No	75	71	79	
Flat stack bottom (%)				
Yes	38	31	50	
No	62	69	50	
Only one timber assortment in stack (%)				
Yes	93	91	96	
No	7	9	4	

* p<0.05; ** p<0.01; *** p<0.001.

Table 8

Description of the measured stacks categorized into the groups A–C based on the effective total measurement time consumption with the Trestima Stack application and statistically significant differences between the stack groups A–C.

	Average (n=60)	Group A <4 s/m³ (n=13)	Group B 4–13 s/m³ (n=27)	Group C >13 s/m³ (n=13)	Stat. significant difference between the groups A–C
Stack location (%)					
Terminal	47	92	48	15	A–B*, A–C***
Roadside landing	53	8	52	85	
Main timber assortment in stack (%)					
Softwood	67	77	67	69	
Hardwood	33	23	33	31	
Stack length (m)	30.4	50.0	31.2	12.4	A–B**, B–C***, A–C***
Stack height (m)	2.20	3.28	2.02	1.58	A–B***, B–C**, A–C***
Ratio of length and height of stack	14.3	15.4	17.1	7.7	A–C***
Stack width (m)	4.08	4.39	4.08	4.02	
Mean diameter of logs estimated by Trestima (cm)	17.2	16.8	17.1	17.3	
Number of logs in stack	2009	4872	1553	584	A–B***, B–C***, A–C***
Solid volume percentage (%)	63.0	62.8	63.1	63.1	
Volume of stack estimated by Trestima (m^3)	199.8	474.5	160.2	52.3	A–B***, B–C***, A–C***
Number of measurement batches	1.6	1.1	1.9	1.2	
Volume of stack in immersion (m^3)	199.3	489.1	151.8	53.6	A–B***, B–C***, A–C***
Measured control mean diameter of logs (cm)	13.6	13.6	13.6	13.3	
Standard deviation of diameter of logs (cm)	5.2	5.9	4.8	5.4	
Air temperature (°C)	+0.0	+0.2	–0.6	+0.0	
When snow, depth of snow cover (cm)	10.2	4.0	7.8	16.3	
Number of Trestima images per stack	3.8	4.5	4.1	2.1	B–C*, A–C***
Photographing distance (m)	6.6	8.9	6.4	5.1	A–B**, A–C***
Successful final Trestima image framing (%)					
Yes	50	54	41	69	
No	50	46	59	31	
Visual obstacle in Trestima image (%)					
Yes	28	15	26	54	
No	72	85	74	46	
Stack covered by snow (%)					
Yes	25	15	19	46	
No	75	85	81	54	
Flat stack bottom (%)					
Yes	38	62	30	38	
No	62	38	70	62	
Only one timber assortment in stack (%)					
Yes	93	100	96	77	
No	7	0	4	23	

* $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Table 9

Description of the measured stacks categorized into the groups A–C based on the effective total measurement time consumption with the conventional stacked timber measurement method and statistically significant differences between the stack groups A–C.

	Average (n=60)	Group A <6 s/m³ (n=14)	Group B 6–17 s/m³ (n=28)	Group C >17 s/m³ (n=15)	Stat. significant difference between the groups A–C
Stack location (%)					
Terminal	47	93	46	7	A–B*, B–C**, A–C***
Roadside landing	53	7	54	93	
Main timber assortment in stack (%)					
Softwood	67	79	61	67	
Hardwood	33	21	39	33	
Stack length (m)	26.4	43.9	27.4	8.9	A–B**, B–C***, A–C***
Stack height (m)	2.54	3.87	2.29	1.79	A–B***, B–C**, A–C***
Ratio of length and height of stack	11.4	12.6	14.2	5.4	B–C**, A–C***
Stack width (m)	4.08	4.31	4.05	3.96	
Estimated mean diameter of logs (cm)	16.2	15.5	16.7	16.5	A–B*
Branchiness and delimbing class (%)					
I	0	0	0	0	
II	98	100	100	93	
III	0	0	0	0	
VI	2	0	0	7	
Crookedness class (%)					
I	0	0	0	0	
II	98	100	96	100	
III	2	0	4	0	
Stacking class (%)					
I	0	0	0	0	
II	100	100	100	100	
III	0	0	0	0	
Solid volume percentage (%)	62.1	62.4	61.8	62.0	
Volume of stack estimated by conventional timber measurement (m^3)	189.1	445.7	145.3	37.4	A–B***, B–C***, A–C***
Number of measurement batches	1.6	1.1	2.0	1.2	
Volume of stack in immersion (m^3)	199.3	490.1	146.3	41.8	A–B***, B–C***, A–C***
Measured control mean diameter of logs (cm)	13.6	13.0	13.9	13.8	
Standard deviation of diameter of logs (cm)	5.2	5.6	5.0	5.5	
Air temperature (°C)	+0.0	+0.0	+0.2	+0.0	
When snow, depth of snow cover (cm)	10.2	4.0	10.0	13.6	
Stack covered by snow (%)					
Yes	25	14	25	33	
No	75	86	75	67	
Flat stack bottom (%)					
Yes	38	64	39	20	A–C*
No	62	36	61	80	
Only one timber assortment in stack (%)					
Yes	93	100	93	87	
No	7	0	7	13	

* p<0.05; ** p<0.01; *** p<0.001.