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Application and accuracy of smart technologies for measurements of roundwood: evaluation of time consumption and efficiency

Stelian Alexandru Borz[1], Andrea Rosario Proto[2,*]

[a]Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, *Transilvania* University of Brasov, Şirul Beethoven 1, 500123, Brasov, Romania; stelian.borz@unitbv.ro
[b]Department of AGRARIA, University *Mediterranean* of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy; andrea.proto@unirc.it

*****Corresponding author

Abstract: Several options are currently available for wood measurement and grading and the manual ones are still widely used in many countries. In the last decade, LiDAR-based methods have been successfully tested in several forestry-related applications, in particular in forest inventory applications, with the main focus on data accuracy. Their usefulness for the quantitative assessment of the harvested wood was less investigated. In particular, studies on resource accounting, including the time needed for various log scanning options, are still missing. In the framework of the Hypercube 4.0 project, this study evaluated and compared the field measurement time consumption of manual (M) and LiDAR-based methods applied to logs characterized by various grouping degrees, namely individual logs, log bunches and piles. Two LiDAR-based platforms were tested, namely a smartphone (S) and a mobile laser scanner (MLS). As these platforms hold different sensing, data storing and processing capabilities, scanning procedures were designed and tested in accordance with their sensing distance capabilities and with the potential of using them in real-world applications. Scanning individual logs by smartphones returned an average cycle time which was lower, though close to that of a detailed manual measurement option, accounting for ca. 1.5 minutes. When scanning log bunches and piles, the cycle time increased to ca. 2.8 and 7 minutes, respectively; however, the scanning efficiency increased also as an effect of the scanning scale from ca. 92 seconds per log, when scanning individual logs, to ca. 67 and 46 seconds per log, when scanning log bunches and piles, respectively. The MLS option was tested for small and big groups of individual logs and log bunches scanned in one turn, as well as for scanning individual piles of logs; in general, these options returned the best efficiency rates, accounting in the best case for ca. 19 seconds per log. Depending on the type of wood measurement application, by their efficiency, smartphone and MLS scanning platforms hold the potential of replacing the manual measurement, particularly when the use of manual procedures is limited. While this study evaluated the time consumption and efficiency of several scanning options, the question on data accuracy remains open and needs to be approached by future studies, some of which are already running in the framework of the Hypercube 4.0 project.

Keywords: wood; measurement options; resources; logs; Industry 4.0

1. Introduction

Wood measurement and grading are important activities in forestry, mainly because they provide the quantitative and qualitative information required for wood market at different points within the wood supply chain. In addition, they form the payment basis for many forestry-related activities such as timber harvesting (Oprea et al., 2007; Picchio et al., 2019; Proto et al., 2020) and they are also required in various types of applications, including forest inventories (Philip M.S., 1994). Depending on the type of forest management, regulations in force and practice rules of different countries, the points at which wood measurement is required may be located within the forest, at the road side (landing), in a wood storage facility, at the gate of a sawmilling factory or directly at a household customer. Particularly, in countries which hold a complex wood supply chain such as Romania (Rauch and Borz, 2020) or Italy (Figorilli et al., 2018), by law and regulations, wood measurement is required to sell the standing timber, wood assortments at the landing, to contract and transfer the harvested wood from landing to a carrier, to contract wood from a storage facility, to check the conformity of transports at the factory gates, to remove suspicions of illegal logging, or to deliver wood to household beneficiaries. Besides forming the basis of transactions between the phases of the supply chain, measurement of the harvested wood is typically used in several scientific applications such as those aiming to run productivity studies.

Manual measurement procedures are well-known and still widely used, standing for the conventional approach to the problem of wood measurement. They are based on a relatively low quantity of information which is typically sampled by measuring the diameter and the length of the logs (Philip M.S., 1994). However, with the transition to the fourth industrial revolution in forestry (i.e., Forestry 4.0), in general, or by aiming at increasing the efficiency within the wood supply on short term, in particular, the amount of data required to document the transactions and the flow of wood is expected to increase in the same way in which the platforms and technology supporting data transaction and flow will change (Müller et al., 2019). This change will make it difficult if not impossible to still rely on manual measurements, even more so when they will be coupled with analogous data storing formats. A convenable solution to producing quantity estimates would be that of integrating the harvester-collected data within the wood supply chains (Müller et al., 2019); in addition, it was found that such data may be used to document several other processes which are important for the forest science and practice (Kemmerer and Labelle, 2021). Yet, for wood measurement applications, such an approach would provide only a partial solution to the problem, for various reasons such as those related to the measurement accuracy (Kemmerer and Labelle, 2021), ownership of the produced data (Hartsch et al., 2021) and the level of harvesting technology used in different countries, which can exclude the use of fully-mechanized harvesting systems on extended areas (Moskalik et al., 2017; Cataldo et al., 2020; Lundbäck et al., 2021) and which ultimately depends on the forest types and silvicultural management (Vusić et al., 2013; Stoilov et al., 2021).

Several other compatible solutions based on light propagation, detection and ranging were developed and tested with the aim of producing wood measurement data. Many of them share a common feature, namely the capability of capturing a cloud of points which can then be used to model and extract relevant features such as the volume of the logs; a contrast between them could be their deployment scale, which depends on their scanning capabilities. Already, photogrammetric techniques coupled with Structure from Motion software have been tested with promising results in estimating the wood volume delivered by trucks (Acuna and Sosa, 2019). While they hold a lot of potential in solving important problems such as estimating the wood delivered to a factory gate, their applicability within forests or in spatially-restricted areas could be limited. Another solution to the problem, which involves mobility, is the use of hand-held laser scanners. A review of Balenović et al. (2021) indicates that these platforms can be successfully used at least in tree inventories, for which the time consumption, efficiency and accuracy estimates were found to be promising. Similar technologies are currently integrated in smartphones, contributing to a significant enhancement in terms of mobility and affordability (Costa et al., 2018). A study of Tomaštík et al. (2017) has evaluated the performance of the Tango technology developed by Google, finding that smartphones equipped with core technologies such as depth perception and motion tracking can be successfully used in forest inventories, showing also a lot of potential by future developments in hand-held mobile technology. In addition, more advanced LiDAR sensors were already integrated in the smartphones and other mobile computing platforms such as those developed by Apple (2021). While this kind of platforms and technologies were tested to collect data and to evaluate their usefulness for forest inventories, to the best of author's knowledge, their application to harvested wood was not fully investigated, meaning that data on their effectiveness is still missing.

This study was carried out in the framework of the Hypercube 4.0 project (2021), which aims at testing and validating the usefulness of the hand-held mobile scanning technologies in the measurement of harvested wood by taking a triple-fold perspective over their performance, namely their accuracy, efficiency and safety. While the expectations on the accuracy would be that of producing reliable estimates due to less occlusion between the sensors and the objects of interests (i.e., logs), the efficiency in terms of cycle time and outputted measurement rates is in question due to the variability in logs' dimensions and their grouping state.

In particular, the focus of this study was on evaluating the cycle time consumption and efficiency of field measurements in a comparative approach that included three grouping states (individual logs, bunches and piles) and three measurement options (manual, smartphone scanning and mobile laser scanning). The rationale for repeating the assessments for gradually increasing grouping states of the logs was that of checking the differences in terms of time consumption and efficiency brought by this factor, in addition to those coming from the instruments used.

2. Materials and Methods

2.1. Study Design and Instrumentation

This study was aimed to test and compare several wood measurement options in the field phase in terms of time consumption and efficiency. A measurement option is hereafter referred as the combination of equipment used for field measurement and the grouping state of the roundwood tested (Table 1). The manual measurement option supposed the use of two teams of two field researchers each, and it was designed to sample the diameters of the logs at a 0.5 m interval, to measure the length, mid-diameter and end-diameters of each log. One team placed the measurement tape on each log, then marked the log by sprayed paint, so as to provide the basis for half-meter diameter sampling. In addition, the same team marked the location of the mid-diameter, and measured and marked as numbers sprayed on the log the end-length of each log in such cases in which it was less than 0.5 m. The second team carried out the actual diameter measurements by a caliper and noted the results on a paper field book, including the end-length of each log and the log ID taken from its tag. Diameters were measured with the arms of the caliper oriented downwards in a plane which was perpendicular to the log axis (0.5 cm accuracy), and the log lengths were measured by a tape at an accuracy of 0.1 m. Although the regular log measurement procedures require either the mid-diameter or end-diameters and log lengths, the choice of this manual measurement procedure was based on getting more accurate estimates by manual measurement.

Table 1. Description of the measurement options tested in the study.

Manual measurement option was tested only for individual logs (M × L, Table 1) having in mind the limited possibility to measure the diameters at the chosen intervals, at the middle and at the ends of the logs when such logs were either bunched or piled. Data produced by manual measurement such as the mid-diameter (hereafter d) and the length of the logs (hereafter l) was used to estimate the volume (hereafter v) of each log, group, bunch or pile of logs.

The scanning equipment tested in this study supposed the use of two data collection platforms, namely a smartphone (Huawei P40 Pro, Huawei, China) and a mobile laser scanner (Zeb Revo, GeoSLAM, https://geoslam.com/) which supports simultaneous localization and mapping technology (SLAM). Forest Design (https://forestdesign.ro/index.php/ro/) Scanner application was installed on two smartphone units in advance of field tests. This application works on Google ARCore, which is provided by Google LLC and governed by the Google Privacy Policy. On Honor/Huawei devices the application works on Huawei AREngine, which is provided by Huawei Device Co., Ltd. and governed by the Huawei Privacy Policy. Currently the application is available for free in Google Play (2021).

The tested platforms are characterized by different capabilities in what regards the sensing distance and the typical workflow and algorithms used to reconstruct objects form the collected data depend mainly on the technology used for reconstruction. As basic information for the two platforms, one can mention that FD Scanner has been designed to run on Android operating systems, giving the possibility to process the data either onsite or at the office. The software holds guiding capabilities which enable and visually informs the user when a scanning process could be considered as complete. In addition, the data collected in the form of point clouds and image files can be used externally to reconstruct the sensed objects. The used MLS platform, on the other hand, enables scanning at considerable distances (up to 30 m for the model used), collects high amounts of data as point clouds referenced in space and can be used for wider-space scanning. The scanned data is stored on memory devices and it can be downloaded and used afterwards in applications able to work with point clouds. The model used during the field tests did not provide a visual guiding system during the scanning applications, therefore the scanning methods were designed so as to cover the foreseen measurement applications and to fully use the sensing capabilities. The use of MLS requires to calibrate the instrument each time a measurement is done, to start and end the scanning process at the same point.

Typically, manual measurement involves at least a team of two operators, while the tested sensor-based methods require just one operator for each measurement scenario. Another difference between the two groups of methods is that the manual ones frequently require pen-and-paper approaches to write down and store the data in the field phase, while the sensor-based ones store the data electronically. Assuming that one needs to estimate the volume of a bunch or pile of wood without any a priori knowledge on logs' volume, manual option has a limited applicability because it is frequently impossible to access each log for diameter measurement. This applies also when one would like to check the measurement accuracy of piled wood which was measured as individual logs, then piled. In addition, compared to sensor-based measurement options, another limitation of the manual method could be the amount of information collected and used to produce the volume estimates, which stands often for one or two diameters and a length of the log.

The measurement methods designed and used in this study were aligned to the sensing capabilities of the two tested platforms (Table 1). As such, the smartphone platform was tested by scanning individual logs (P × L), bunches of logs (P × B) and piles of logs (P × P). Typically, a bunch of logs contained 2 to 4 logs which were placed near one other while a pile of logs contained 7 to 14 logs placed near and over each other in a number of maximum three rows.

2.2. Data Collection

Field data collection activities were carried out in September of 2021 in a wood storage facility managed by the National Forest Administration - RNP Romsilva through the Regional Forest Directorate of Maramureş. The storage facility is currently used to store broadleaved and resinous wood harvested from the surrounding forests in the form of piled logs until selling it to the final customers. There were two storage areas designated for broadleaved (hereafter S1) and resinous (hereafter S2) wood, respectively, in which piles of wood were available in various lengths and diameters.

Part of the data needed for this study was collected in the form of video files by the use of a GoPro Hero 5 (GoPro Inc., https://gopro.com/en/us/) video camera which was placed at a location from where all the storage areas were readily visible. The device is equipped with a colour LCD screen which helped in orienting the field of view towards the storage areas, and it was powered by an external battery so as to cover by video recording all the activities developed in each day. The collected video files had a duration of ca. 20 minutes each, they were stored on a memory card and downloaded and ordered into a computer at the end of each day.

A rubber-tired loader was used in S1 and S2 to mechanically move the logs from several piles and to arrange them spaced at ca. 1.5 m from each other (Figure 1a,b). In S1, the logs were placed on the ground in two parallel groups (hereafter G1 and G2) leaving a space of approximately 2 meters between them (Figure 1a) to make possible the movement and scanning by MLS; G1 and G2 contained 27 and 29 logs, respectively. In S2, a single group of logs (hereafter G3) was placed on the ground, containing a number of 35 logs. Following this arrangement, manual measurements were carried out for each log following the procedures described in section 2.1. Once the data was collected by manual measurement, scanning activities by the means of smartphones were carried out in one replication for all the logs available on the ground (56 broadleaved in S1 and 35 resinous in S2). Phone scanning supposed the setup of scanning application, operator's walking around the log at low speed while directing the camera towards the log at a variable distance (average of ca. 1 m), saving the results and waking to the next log. The MLS equipment was used to scan smaller groups of logs from G1 and G2. For doing so, subgroups of 4-6 logs were delimitated in G1 and G2 by ground-marking, then the device was used to walk around them and to scan them from ca. 2 m by starting and ending the process on the same point (a horizontally levelled platform was used). Following these activities, the MLS equipment was used to scan all the logs from G1, G2 and G3 (BL option, Table 1), respectively, in one turn and by following a similar procedure. Procedurally, scanning by the MLS device supposed the setting up of the equipment, the effective scanning by moving around the groups of logs, saving the data and moving (including the levelled platform) to the next group of logs.

Once these measurements were done, the loader was used to bunch the logs from all the groups (G1-G3) so as to form bunches of 2-4 logs (Figure 1c), resembling the payloads typical to some forest operations. By this kind of grouping, the spaces available between the bunches varied from ca. 1 to 5 m. Accordingly, the field book was updated to indicate which log belonged to which bunch. For this form of log grouping, in all storage areas the phone scanning activities were replicated twice (i.e., by two different operators), while the MLS scanning activities were replicated once (i.e., by a single operator), involving a single scan for each storage area. After the completion of all measurements done for the bunches, the loader was used again to build wood piles in both storage areas. In total, ten wood piles were formed of which five in S1 and five in S2. Following this kind of grouping, the distance between the piles increased to up to 10 m. The field book was updated accordingly to keep the track of logs' IDs in each wood pile. Then each pile was scanned by the means of smartphones (two replications) and MLS (one replication).

To summarize, scanning by phone of individual logs in each storage area (P × L, S1 & S2) was replicated once because the scanning approach was straight forward, while scanning of bunches (P × B) and piles (P × P) was replicated twice in each storage area (S1 & S2) given that the scanning approach taken by different individuals could vary. The MLS platform was used to scan small groups of individual logs (MLS × SL, 4 to 5 logs per group in S1), big groups of logs (MLS × BL, 3 groups of 27, 29 and 35 logs respectively in S1 and S2, respectively), groups of bunches (MLS × GB), and individual piles of logs (MLS × IP, 10 piles of logs) in one replication (i.e., one measurement done by a person), given that the scanning approach supposed mainly the movement around each feature of interest (group of logs, group of bunches or individual pile). While all the bunches from S1 and S2 were scanned by phone and MLS, respectively, due to a data storage malfunction only the video footage from S2 (14 bunches) was available for the assessment of these measurement options (Fig. 2).

Fig. 1. Examples of wood arrangement during the field tests: a – Storage area 1 (S1, broadleaved), individual arrangement of logs in two groups (G1 and G2), and phone scanning activities; b - Storage area 2 (S2, resinous), individual arrangement of logs in one group (G3) and phone scanning activities; c – Storage area 1 (S1), bunched arrangement of logs in group 2 (G2), d – Storage area 1 (S1), an example of piled arrangement of the logs.

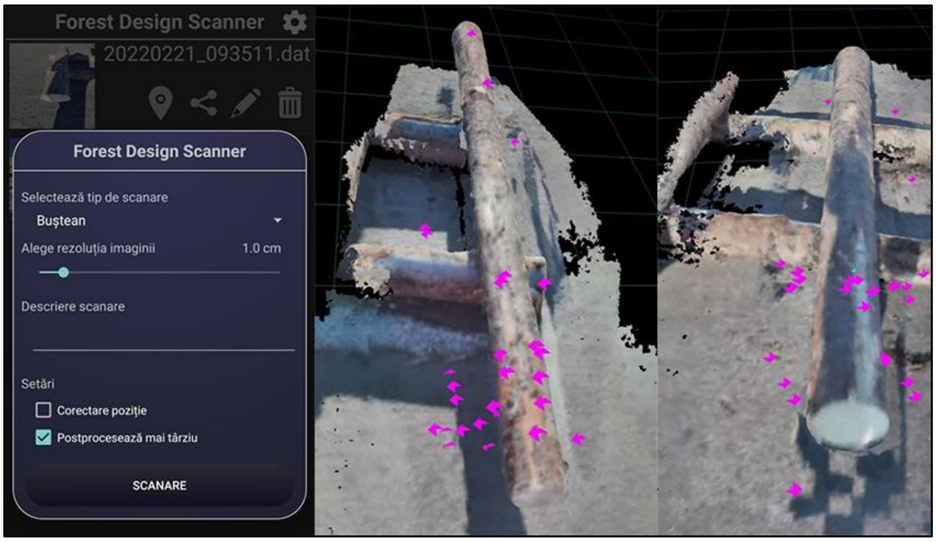

Fig. 2. A screenshot during the individual log scanning by phone.

2.3. Data Processing and Statistical Analysis

The manual data, as collected in this study, required a transfer by manual input into a spreadsheet, which may be followed by the use of more or less complicated calculation algorithms to estimate the volume. Volume estimation by traditional methods would require a specific data organization to enable the use of mid- and end diameters of the logs as well as their length. More advanced methods which are based on the use of all the diameters, half-meter length and end length would require data input into a spreadsheet on either columns or rows, followed by the use of more advanced volume calculation algorithms able to account for the measured parameters and their measurement locations. Nevertheless, the data collected manually was typically tabulated for further processing and the diameters corresponding to each log and sampling position were transferred in the rows of Microsoft Excel® (Microsoft, Redmond, WA, USA, 2013 version) spreadsheets. Both scanning platforms, on the other hand, may output the data in formats which are quite similar to each other but different from those produced by manual measurement, namely files containing the point clouds and images or media files that are automatically taken during scanning. Such data can be processed later by either using Structure from Motion (SFM) algorithms or by software which enables working with point clouds.

Manually collected field data such as the length (l) and mid-diameter (d) of each log was used to estimate the volume per log (v) by the Huber’s formula, then all the data was organized at several levels of aggregation such as the individual logs, individual logs contained in small and big groups, respectively, logs contained in bunches and logs contained in piles. This sorting helped in accounting for the number of logs contained in bunches and piles as well as in estimating the volume of bunches and piles as variables needed in the assessment of measurement’s cycle time and efficiency. Video footage was analysed in detail to extract the time consumption, as specific to each option, to the nearest second. Given the type of activities taken into study, in most cases it was possible to organize the observed tasks into work cycles containing specific work elements. The approach used in this study was that of removing all the delays, including those caused by mechanical wood arrangement, and keeping into analysis only those categories of time consumption which were explicitly linked with the measurement options taken into study. For guidance and for choosing the categories of time consumption so as to enable comparison, the work of Kanawaty G. (1992) and Björheden et al. (1995) were used as reference.

The analytical part of the study aimed at (*i*) developing the descriptive statistics for the log, bunch and pile variables, (*ii*) developing the descriptive statistics of time consumption for each option and (*iii*) estimating the efficiency and productivity of the tested measurement options. In the scope of the study, the efficiency was mainly estimated as the time needed to measure a log, bunch or pile, although the volume was used as well as a unit for efficiency assessment. The same approach was used to estimate the productivity of measurements as a performance metric. For guidance and for choosing the categories of time consumption so as to enable comparison, each work cycle was divided following the terminology "Forest Work Study Nomenclature" (Björheden et al. 1995). For the first and second objectives, a normality check of the data was carried out by the means of Real Statistics add-in software (2021) running under Microsoft Excel®. Since the data was generally found not to meet the normality assumptions by the means of Shapiro-Wilk tests, the statistics of the log-related variables (*l, d, v*) were described by absolute frequencies on categories and by the minimum, maximum, mean, standard deviation and median values. Accordingly, the time consumption variables were described at elemental level for each option and replication and a summarization of time consumption was provided when the study included replicates. In addition to the descriptive statistics used for the log variables, the elemental and cycle-wise time consumption was described by the coefficient of variation to be able to better describe the variability in time consumption between the measurement options. Also, the elemental time consumption was described by its relative share in the work cycle of a given option. While the scope of the study was that of comparing the cycle time and efficiency of the tested measurement options, additional time consumption models was developed where appropriate and reported in the appendix section of the study, along with their statistics characterizing their predictive power and presence or absence of heteroskedasticity. Checking for heteroskedasticity was done by plotting the squared residuals of the cycle time against the values predicted by the models and by using the Breusch-Pagan test, as described in Gujarati (2011). Estimation of the main performance metrics such as the efficiency has followed the guidance given in the work of Björheden et al. (1995), and it was based on the delay-free time.

3. Results

3.1. Descriptive Statistics of the Logs, Log Groups, Bunches and Piles

In total (Table 2), 91 logs (56 logs of beech and 35 logs of spruce) were manually measured following the procedures described in section 2.1. On average, the length was smaller in the case of broadleaved logs (data not shown herein). Mid-diameter (*d*) did not show very high differences between broadleaved (31 cm, on average) and resinous (34 cm, on average) logs. The average estimated volume for broadleaved logs was of 0.43 m^3 while for the resinous logs it was of 0.79 m^3 (data not shown herein). The sample taken into study accounted for a total of 51.7 m^3, of which 24 m^3 were broadleaved logs and the rest of 28 m^3 were resinous logs. In the sample, dominant were the logs having lengths of 3 to 4, 5 to 6, 6 to 7 and 9 to 10 m, which accounted together for more than 50% of the sample (Figure 3a). An important share of the logs had mid-diameters in between 30 and 35 cm (31%), and most of the logs within the sample had mid-diameters higher than 25 and less than 40 cm (85%, Figure 3b). In terms of volume, one third of the logs (33) had a volume in the range of 0.25-0.50 m^3, and most of the logs had a volume of less than 1 m^3 (Figure 3c). For the G1, G2 and G3 groups of logs, the mean log lengths were of 5.3, 6.3 and 8.5 m, respectively; mid-diameters averaged 31, 31 and 34 cm while the mean volume of a log per group was of 0.40, 0.46 and 0.79 m^3, respectively.

Table 2. Descriptive statistics of the logs' length, mid-diameter and estimated volume.

Table 3 shows the main descriptive statistics of bunches from the third (G3, resinous) group of logs. The number of logs within a bunch varied between 2 and 4, averaging 2.5 logs per bunch. The maximum length of the bunch, which was that of the longest log in each bunch, was between 5.2 and 12.3 m, averaging ca. 10 m. The minimum and maximum mid-diameters of each bunch were those corresponding to their respective logs within a given bunch. On average, the mid-diameter of the logs within a bunch varied in between 27 and 44 cm, averaging 34 cm. Accordingly, the average volume per bunch was of 2 m^3, and it varied between 1.2 and 2.9 m^3. The main descriptive statistics developed for the pile-level of aggregation are given in Table 4. There were formed 10 wood piles in total, of which half were of broadleaved and half were of resinous logs.

Table 3. Descriptive statistics of the bunches from G3.

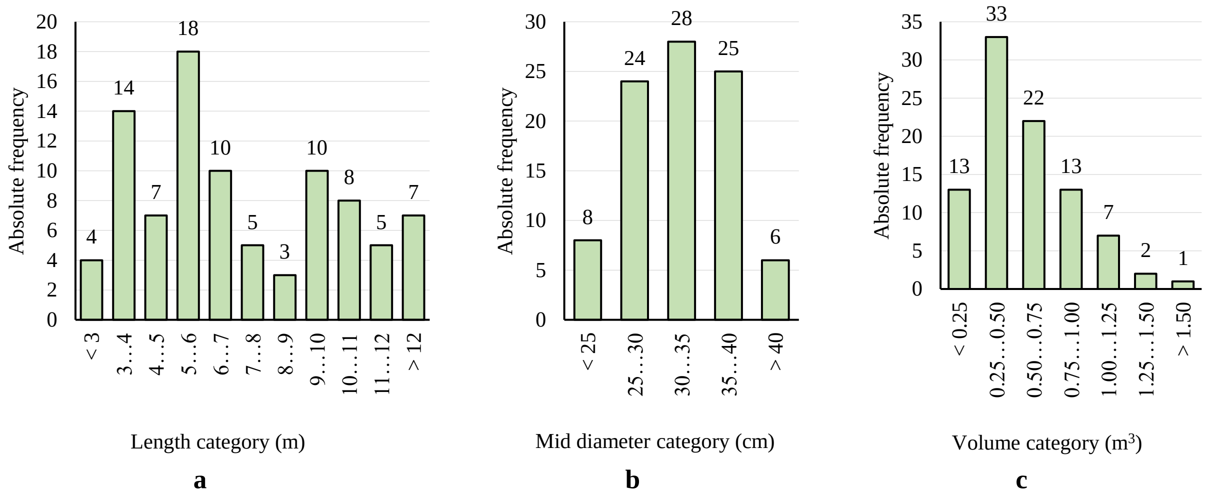

Fig. 3. Absolute frequencies of the length (a), mid-diameter (b) and volume estimates (c) on categories for the sample of logs taken into study.

Table 4. Descriptive statistics of the piles.

On average, the number of logs in the broadleaved piles was of 11, while in the resinous piles it was of 7, averaging 9 logs at the pile sample level. The maximum length of a pile, which was calculated the same way as in the case of log bunches, averaged 9 m. However, the maximum length averaged 8 m in the case of broadleaved and 11 m in the case of resinous piles. The mean volumes per pile were different between broadleaved and resinous piles, averaging 4.8 and 5.5 m^3, respectively. At the pile sample level, the mean volume was of 5.2 m^3.

3.2. Measurement Time

Table 5 shows the main descriptive statistics for the elemental and cycle-wise time consumption in the case of manual measurement option. A complete manual measurement work cycle (MMCT) accounted, on average, for 99 seconds, of which nearly 48 seconds were needed for log marking and the rest (approximately 52 seconds) for diameter measurements. Marking the log by painting (MPL) took most of the time in a log measurement work cycle (LMCT, ca. 67%), while measuring the diameters along the log (MDL) took most of the time (ca. 76%) within a diameter measurement work cycle (DMCT). The only significant independent variable that explained the work cycle time consumption for log marking (LMCT), diameter measurement (DMCT), manual measurement (MMCT) and the phone scanning (LSCT) was the length of the measured log (Figures A1-A2). It explained the variation of the above-mentioned work cycle times in proportions of 54 (R^2=0.54), 81 (R^2=0.81), 77 (R^2=0.77) and 27% (R^2=0.27), respectively. At the work cycle time level, the model developed for the phone scanning option (LSCT) was found to meet the assumption for homoskedasticity, which was not the case of MMCT model (Figure A3). Descriptive statistics of the time consumption for individual log scanning by phone are given in Table 6. Within a scanning work cycle (LSCT), phone setup and the effective log scanning (PSL) took most of the time, accounting for close to 80%. A log scanning work cycle (LSCT) averaged 92 seconds, which was less, though close to the cycle time of manual log measurement option (MMCT, Table 5).

Table 5. Descriptive statistics of the time consumption for manual measurement option.

Compared to the manual option by the means of the coefficient of variation (CV), the variability within the work cycle time for the individual log scanning by phone was less (CV = 27). However, no significant dependence relations were found to explain the variability of phone scanning cycle time as a function of the log length. A number of 14 log bunches were scanned by phone twice (each of them by a different person). The main results of the time consumption are shown in Table 7. Compared to the individual log scanning by phone, setup and effective scanning (PSB) took more time, accounting for 90 (R1) and 95% (R2), respectively. On average (O, Table 7), this work element accounted for 93% of the work cycle time. These differences in time share and in the work cycle time are related to the typical way in which different operators may approach the scanning process. Compared to the individual log scanning by phone, bunch scanning work cycle time (BSCT) averaged to nearly 152 and 183 seconds for the first (R1) and second (R2) replicate, respectively, which was significantly more time consumed in the process but less time consumed per piece (bunch size of 2-4 logs). The averaged data coming from the two replicates indicated an average work cycle time of close to 167 seconds.

The time needed to scan the bunches of logs individually in S2 was, on average, of 1299 seconds, while to individually scan the logs in the same storage area, the time needed was of 3321 seconds (data not explicitly given herein). Similar to the option of individual log scanning by phone, the coefficient of variation had a lower value as compared to the manual measurement, indicating therefore less variability in the work cycle time. Attempts were taken to explain the work cycle time as a function of the maximum log length, which was assimilated to the length of the bunch, and of the number of logs within a bunch. However, no significant dependence relations were found between these variables taken into study.

In Table 8 are given the main descriptive statistics for the option of scanning piles by the phone. Ten piles were scanned in two replicates, and returned average work cycle times of 335 (R1) and 509 seconds (R2) per pile, respectively. Compared to the option of scanning bunches of logs, pile scanning excluded the time needed to move between the piles. However, it included the time needed to setup, scan and save the data. There were important differences between the two replicates, with the second one requiring ca. 50% more time for an average work cycle. On average (O), a work cycle time accounted for 422 seconds in conditions in which the number of logs per pile varied in between 7 and 14 (Table 4). Accordingly, the time spent per piece was less than that estimated for the bunch scanning option.

Results of the MLS scanning options are summarized in Table 9. For small groups of individual logs (SL, 4-5 logs per group), a scanning work cycle (SWT) by MLS took, on average, close to 6 minutes. The effective scanning (S) accounted for less than 40% of the work cycle time, a figure which was similar to that of scanning individual piles of wood (IP), and as the groups of logs became bigger, the effective scanning (S) increased as share in the work cycle time, which held true also for scanning groups of bunches. The average work cycle time per pile was of 3.5 minutes. Similar to the phone scanning options, the intra-work cycle variability was lower (coefficients of variation of ca. 20). Scanning individual piles by MLS took, on average, less time per work cycle as compared to the aggregated data (O) of the pile scanning by the phone option.

Table 6. Descriptive statistics of time consumption for individual scanning of logs by smartphone.

Table 7. Descriptive statistics of time consumption for bunch scanning by smartphone.

Table 8. Descriptive statistics of time consumption for pile scanning by smartphone.

Table 9. Descriptive statistics of time consumption for MLS scanning options.

3.3. Performance Metrics

Figure 4 shows the efficiency estimates which were calculated based on the time consumption and the number of logs or the volume of wood for each measurement option. Accordingly, Table 10 summarizes the performance of the tested measurement options in terms of productivity measured in logs, bunches, piles or volume per hour. When measuring individual logs (L), the time spent per log and m^3 of wood returned close values for the manual (M) and phone-based (P) options, and the phone-based option required less time as compared to the manual one. As more logs were grouped together by bunching (B) or piling (P), the time needed by phone scanning option decreased. For instance, the time required per log was two times less when scanning piles (P × P) in comparison to that spent to scan individual logs (P × L). Consequently, scanning bunches of logs (P × B) accounted for an intermediary value.

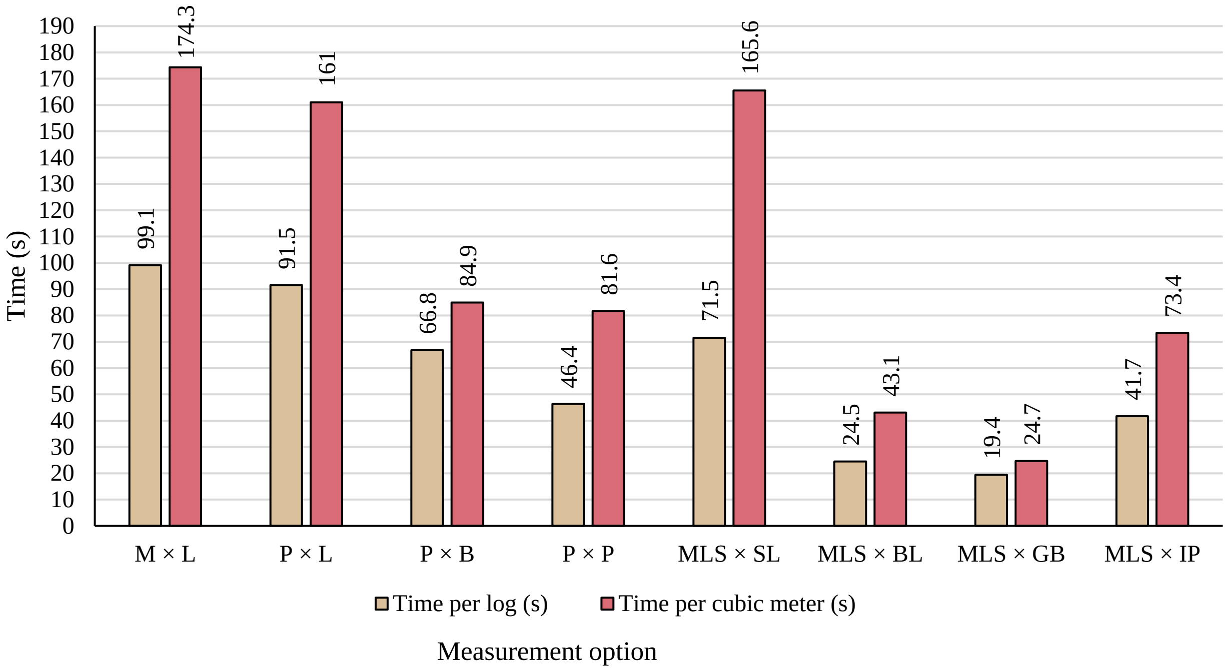

Figure 4. Efficiency of the tested measurement options.

Scanning by MLS took, in most of the cases, the least time as compared to the other options, which was an effect of scale. However, preparing the equipment and saving the data could be the most time-consuming element, therefore the bigger the groups of logs the better the efficiency. As such, scanning together big groups (BL) of individual logs (G1 = 27, G = 29, G3 = 35) took almost three-fold less time compared to scanning small groups (SL) of individual logs (4-5 logs per group). At the log level, the time consumption was lower compared to the phone-scanning option while the time needed per volume was similar. Scanning together all the bunches (GB) seemed to be the most efficient in the compared set of options, being comparable only to scanning big groups of logs (BL) by MLS. Finally, scanning individual piles (IP) by MLS was comparable in terms of efficiency to scanning individual piles by phone.

The productivity figures followed a similar trend, as shown in Table 10. Manual measurement option (M × L) was comparable with the individual scanning of logs by smartphone (P × L), accounting for 36 and 39 logs hour^{-1}, or for 21 or 22 m^3 hour^{-1}, respectively. The most performant option was the MLS scanning of bunches (GB) in one turn (185 logs hour^{-1} or 146 m^3 hour^{-1}) followed by scanning by MLS of big groups (BL) of logs (147 logs hour^{-1} or 84 m^3 hour^{-1}).

Table 10. Expected productivities for the tested wood measurement options.

4. Discussion

For wood measurement applications, the usefulness of mobile hand-held LiDAR based methods was evaluated mainly in forest inventory applications. For hand-held mobile laser scanners (MLS) the review study of Balenović et al. (2021) has emphasized that the results obtained so far are promising, although the generalization in use of MLS for forest inventory applications still requires more research to clarify what data acquisition protocols would be the best, to tackle the occlusion problems and their effects on the data completeness and last, but not least, to evaluate the variability of measurement performance as an effect of contrasting field conditions that may be encountered in various forests types. As a fact, besides the accuracy, completeness and other technical performance metrics, which are important to validate this kind of technologies in forest- and forestry-related applications, cycle time consumption and efficiency in terms of resources used are important factors to be considered, as similar to many other product-oriented or man-made systems (Wasson C.S. 2006).

Based on the lack of studies addressing the problem of harvested wood, this study is justified and brings reference data on the scanning cycle time and efficiency of two LiDAR-based platforms. The results reported herein are even more so important as the wood supply chain includes a flow of commodities (i.e., wood) and supposes the information exchange on the quantity and quality of the wood; as such, any delay specific to a phase has the potential of creating bottlenecks for others in the supply, which ultimately will be reflected in the delivery costs, and will cause time and money losses. Although some of the bottlenecks may be removed by various scientific methods applied to the supply chain analysis (i.e. Kelly and Germain, 2020), wood measurement is typically a step which is difficult to reallocate or reschedule, because it often stands as an interface between different stakeholders which operate within the wood supply chain. In many ways, technology development in the wood supply chain is nowadays consistent with the foreseen visions, meaning that in many parts of the world we already see a dynamic allocation of functions and information between the cells of the supply chain (Heinimann H.R, 2007). Also, to preserve the sustainability of the wood supply, changes in the work systems and technologies used are needed (Figorilli et al., 2018; Proto et al., 2020) and some of them are already implemented in practice. These visions support the need of changing the approach used in wood measurement activities.

In the above context, the results reported herein are consistent with the research done over several mobile hand-held LiDAR based platforms and methods used in forest inventories in the sense that, in general, they outperformed the manual options in terms of efficiency (Ryding et al., 2015; Bauwens et al., 2016; Giannetti et al., 2018; Oveland et al., 2018; Chen et al., 2019; Gollob et al., 2020). For instance, the measurement performance of smartphones as scanning platforms was reported to be of 20 to 25 m^2 min^{-1} when scanning plots of 500 m^2 in forest inventory applications (Tomaštíc et al., 2017). Accordingly, MLS scanning can be done at a rate of 50 (Bauwens et al., 2016) to 75 (Oveland et al., 2018) m^2 min^{-1}. Most of these options were tested by scanning at the speed of walking, which was imposed by the mobility conditions specific to the forests. In addition, the performance outcomes in terms of time consumption and efficiency may depend largely on the shape and size of the plots, scanning patterns adopted, type of forests within the plots and stem density.

In this study, scanning individual logs by smartphones returned an average cycle time and an efficiency which were better though similar to those of a detailed manual measurement. Yet, the manual measurements were done so as to provide a comparison basis as reliable as possible for the accuracy studies which are under development within the Hypercube 4.0 project. One can argue that using the regular procedures for manual measurement would naturally lead to a lower cycle time consumption and to an increased efficiency, which may hold true. For instance, by summarizing only the time required to move to the log and to measure the log length and mid-diameter by a team of two people (Table 5), the cycle time would be of ca. 30 seconds, meaning that the main evaluated performance metrics would be of 30 seconds per log or 120 logs per hour. However, as demonstrated by many other studies on the topic, the information quantity which is typically produced by the two options (manual and scanning) is different. For instance, manual measurements rely on generalizations and estimates which are based on the measurement of a diameter and of a length of the log. In contrast, smartphone-based methods were described to be able to produce millions of points (i.e., 7.65 to 21.12 million of points for circular plots of 500 m^2), which is likely to better reflect the shape and the volume of the logs. MLS platforms, on the other hand, are able to produce very well documented data in terms of points collected per second (Balenović et al., 2021).

Another difference is that manual measurement would typically require more than one worker, as somebody needs to write the data on paper or to store it in another format, making it difficult for a single person to handle the tape, caliper and a given data storing platform in one pass; hence, the hourly operating costs could be higher as compared to the phone scanning option. Accordingly, the use of analogous data storing formats will require more office work for data transcription in electronic formats.

In this study, scanning was done by aiming to provide a better coverage in terms of collected points and to comply with the visual guiding systems embodied in the smartphones. In many instances, this supposed a very low walking pace. Therefore, increasing the movement speed, as opposed to that used in this study, will possibly shift the estimated efficiency metrics in the sense of producing lower cycle times and higher scanning efficiencies. However, this will depend largely on the accumulated experience in scanning tasks as well as on the developments in mobile data storing and processing technologies, which need to be balanced with the results which one can obtain in terms of accuracy. Accordingly, the differences in efficiency between the tested options were, in fact, an economy of scale, meaning that by increasing the grouping state of the logs better efficiency figures could be obtained; although the time needed to scan the logs was generally higher as their grouping state changed from individual to bunched and from bunched to piled, the latter options became more efficient in terms of unit time consumption. Perhaps the result reflecting at full extent this behavior is that estimated for scanning groups of bunches by MLS, which required a single setup and data saving in the scanning equipment and a scanning approach that aimed at collecting the data in one turn. Consequently, if piles of wood would be available on distances that would support scanning in one turn, the efficiency would increase accordingly by the means of two mechanisms, namely a shorter time needed for setup and saving and more wood available for scanning in one turn. However, the procedure would need a careful design to limit the drift of the collected datapoints, therefore it could require the deployment of scanning on limited spaces.

For both models (MMCT, LSCT), it was found that the cycle time consumption depended on the log length. Judging by the coefficient of determination, only the manual measurement provided results suitable for developing a powerful predictive model in terms of explained variance. However, this model failed the test for homoskedasticity, which may be the effect of lacking additional variables affecting the variability in data. Nevertheless, tests for significance when developing the model have indicated that none of the rest of measured variables could be used as supplementary predictors of the MMCT. Failing to develop more powerfulmodels which to explain to an acceptable extent a similar dependence relation for smartphone scanning of individual logs could be attributed to the different techniques used by the two measurement options. As such, in manual measurement, the work elements were characterized by the same succession in a work cycle, which was straightforward and depended mainly on the distances on which the operators continuously moved along the logs. Phone scanning, on the other hand, supposed movements on both sides of the logs as well as unpredicted forward and backward movements which were guided by the completion of tasks displayed on the phone's screen. These movements randomly affected the time needed to move along both sides of the logs, therefore the cycle time; the same happened when scanning by phone bunches or piles of logs. For some piles, the scanning technique supposed scanning over the pile, which was an adaptation so as to potentially collect more accurate data. Assuming that the collected data would provide enough accuracy and for safety reasons, in real world applications, the piles will need to be scanned by walking around them, therefore the cycle time of this option could be lowered.

The general trend within the wood supply chain is that of gradually grouping the logs, starting from the felling site and ending with the storage facilities (Proto et al., 2020), which is required to save the available storage space and to increase the effectiveness of transportation. As such, accurate measurements of individual logs by manual means can become increasingly less accessible throughout the typical wood flow from the forest to the industries, particularly when such logs are placed in unarranged piles, making it difficult to access their end-diameters and lengths by measurement. In such cases, the information provided by the use of LiDAR-based platforms could prove to be value-adding and could stand for an extension in measurement capabilities. The extent at which bunching and piling affects data collection by occlusion needs to be tested, and studies are under development to clarify this aspect within the Hypercube 4.0 project.

As a fact, according to the results of this study, by increasing the grouping of the logs, an economy of scale may be achieved in the scanning activities, meaning that less time is required per unit of measurement (log, bunch, pile or cubic meter, Figure 3), or more units can be scanned in a given unit of time (Table 10).

The same hold true for the MLS option which proved to be the most efficient one in most of the cases. However, the option of scanning large groups of logs is highly unlikely to occur in practice, as the logs are typically distributed over small-sized areas at landings or in storage facilities. Unless one attempts to do such measurements in the forests following tree felling and processing, the option holds less applicability for the practice. Yet, it can provide enhancements in reliability of data needed for comparison with other options in terms of accuracy. On the other hand, scanning bunches of logs by MLS in one turn or individual piles may be useful for the wood stored at both, landings and storage facilities. These options returned excellent results in terms of efficiency and could be extended to piles which are higher than those scanned in this study (maximum 1.5 m). As in this study preparing, moving and saving were work elements which accounted for a considerable amount of time, it is likely that the option of scanning piles in one turn would enhance the scanning efficiency. This scanning option could be applicable to landings and log storage facilities.

Availability of more logs for running this efficiency study would have brought many benefits in terms of precision and better inferences of the performance metrics reported herein. Accordingly, one limitation of the study is that of having used a limited sample of logs to produce the estimates. However, the practice of science is often imposing such limitations which are ultimately dictated by the amounts of resources needed to run the experiments (Kanawaty G.., 1992). For this study, the logs had to be taken from already formed piles and distributed in the arrangements required by the experimental design, which was done by the help of the storage facility's staff, immobilizing some of the workers for given amounts of time. In addition, it required the use of a loader, which supposed consumption of fuel and machine unavailability for regular tasks. To improve the precision of estimates, future studies should be developed to account for the time consumption as specific to other or similar wood measurement scenarios. Although the estimates of this study were produced based on data collected in a storage facility, they could easily resemble the measurement conditions as specific to landings. However, the reliability of estimates for log measurement within the forests, or for contrasting conditions in terms of log lengths, needs to be questioned, which is just another reason for running additional studies to reflect the variability brought by such conditions.

Another limitation of the study is that data on scanning accuracy was not available so as to see if the used scanning options would produce similar wood estimates as compared to the manual measurement. Accuracy of the tested options is currently being assessed by the objectives and activities developed within the Hypercube 4.0 project, including the time consumption and efficiency of data processing methods. Meanwhile, compared to the ground truth, the errors generated by similar scanning options were found to be of up to 2 cm (Tomaštíc et al., 2017) for phone applications and of up to 4 cm for MLS applications, with the latter depending on the diameter of the scanned trees (Balenović et al., 2021). Collecting time study data by video recording may provide many benefits, including that of having stored the real sequence of the observed events, data retrieval and reviewing at any time (e.g., Borz et al., 2014; 2021); the major problem in running video-supported time studies is that of a high amount of resources spent (Muşat et al., 2016). For this study, one can mention that it was difficult to separate very accurately the time elements of equipment setup and data saving, as the perspective over those activities was that viewed by the camera and not by the eyes of the operators. Therefore, the estimates on time consumption could have been biased to some extent for these tasks.

5. Conclusions

Based on the results of this study, the use of mobile hand-held data collection platforms equipped with LiDAR technologies has a lot of potential in applications of measuring harvested wood when their evaluation is focused on time consumption and efficiency. In terms of average cycle time, the results indicated that smartphone platforms returned figures which were similar to those of a detailed manual measurement. Even when manual measurement is to be done conventionally (i.e., by measuring the mid-diameter of the log and log's length) scanning by smartphones may return good results in terms of human resource allocation given the fact that, as opposed to manual measurements, they are handled by a single operator. Nevertheless, the practice of manual measurement may require a more detailed diameter sampling procedure as the length of the logs increases (i.e., tree lengths). In such cases, the gain in efficiency could be even higher when using smartphones. Also, an efficiency increment was observed as an economy of scale, meaning that as the number of logs grouped together (bunches or piles) increased, the scanning time per log decreased. Mobile laser scanners can provide more detailed data by their sensing capability. However, scanning groups of individual logs could make sense only for scientific purposes as opposed to scanning groups of bunches or individual piles, which may be applicable to landings and wood storage facilities. These log grouping options returned some of the best efficiency rates. Yet, at the time of completing this study, no information was available to check the accuracy of scanning options as compared to the manual measurement. Therefore, the validity of the estimates given herein still needs to be assessed based on accuracy performance metrics. What can be already inferred in addition to their efficiency is that LiDAR based methods could provide better safety conditions compared to manual measurement as they do not require any contact with the measured logs. Besides evaluating the efficiency of LiDAR-based scanning applications in wood measurement, the results of this study may be of help in designing similar studies and in allocating resources when running such studies. In conclusion, similar to many other forest-related operations, wood measurement should meet the safety requirements; in fact, measuring unstable logs by manual means should be avoided. However, such circumstances may be specific to forests as well as to the logs stored at the landings or in storage facilities (wood piles). Although the safety requirements were not explicitly addressed by this study, one needs to consider that scanning as an option could provide the best safety conditions, as it does not require a contact of the measurement device with the logs.

CRediT authorship contribution statement

Stelian Alexandru Borz: Methodology, Investigation, Software, Formal analysis & Writing - original draft.
Andrea R. Proto: Methodology, Investigation, Writing - review & editing.

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Declaration of Competing Interest

The authors report no declarations of interest.

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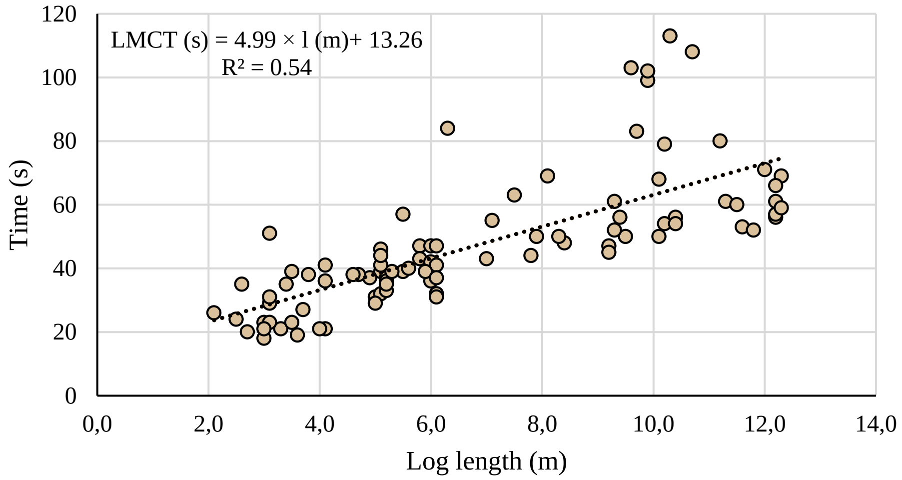
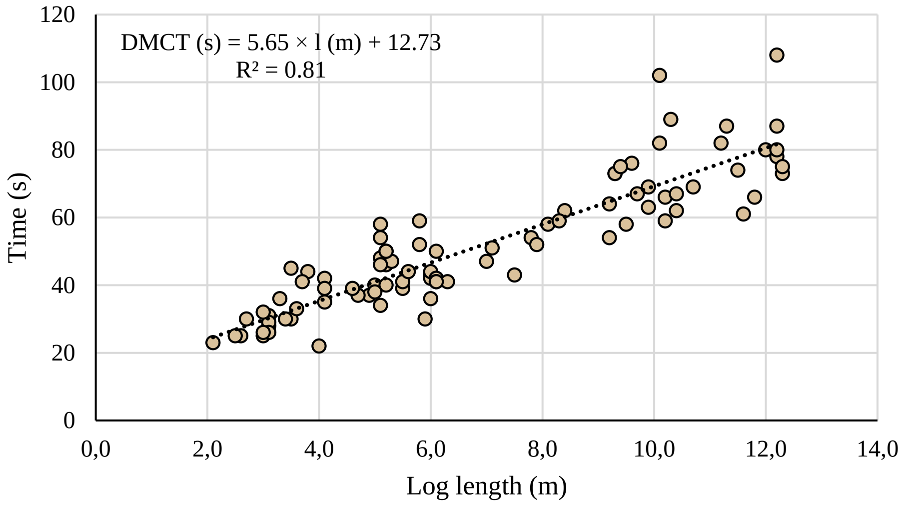
Data Availability Statement

Data supporting this study may be provided on a reasonable request to the first author of the study.

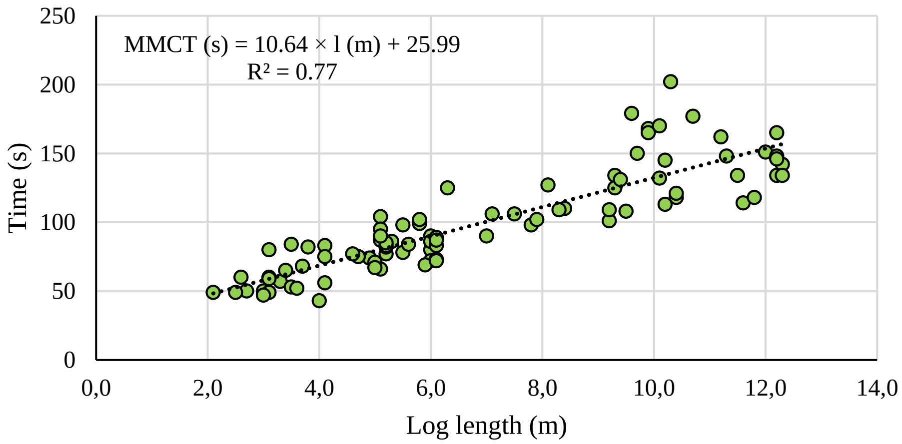
Appendix A



a



b



c

Figure A1. Time consumption models for the log marking cycle time (a), diameter measurement cycle time (b) and manual measurement cycle time (c).

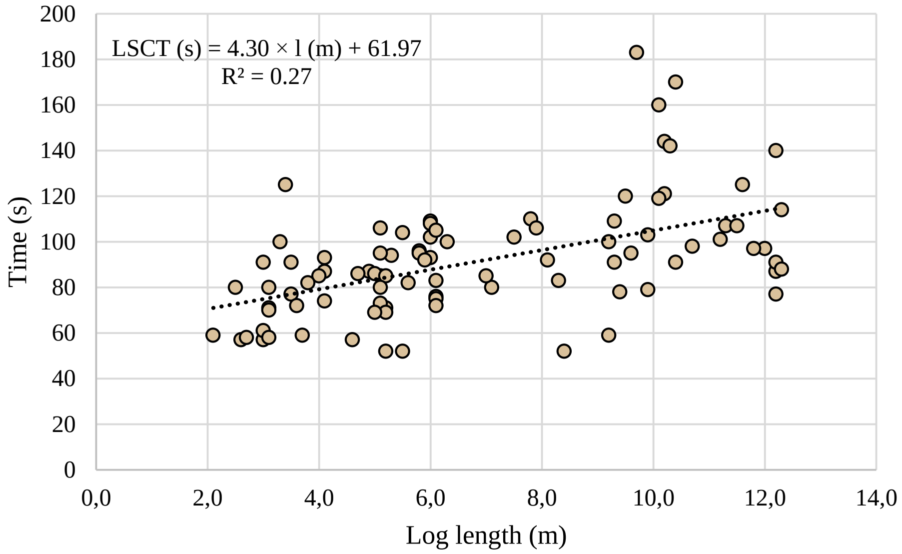


Figure A2. Time consumption model for the individual log phone scanning cycle time.

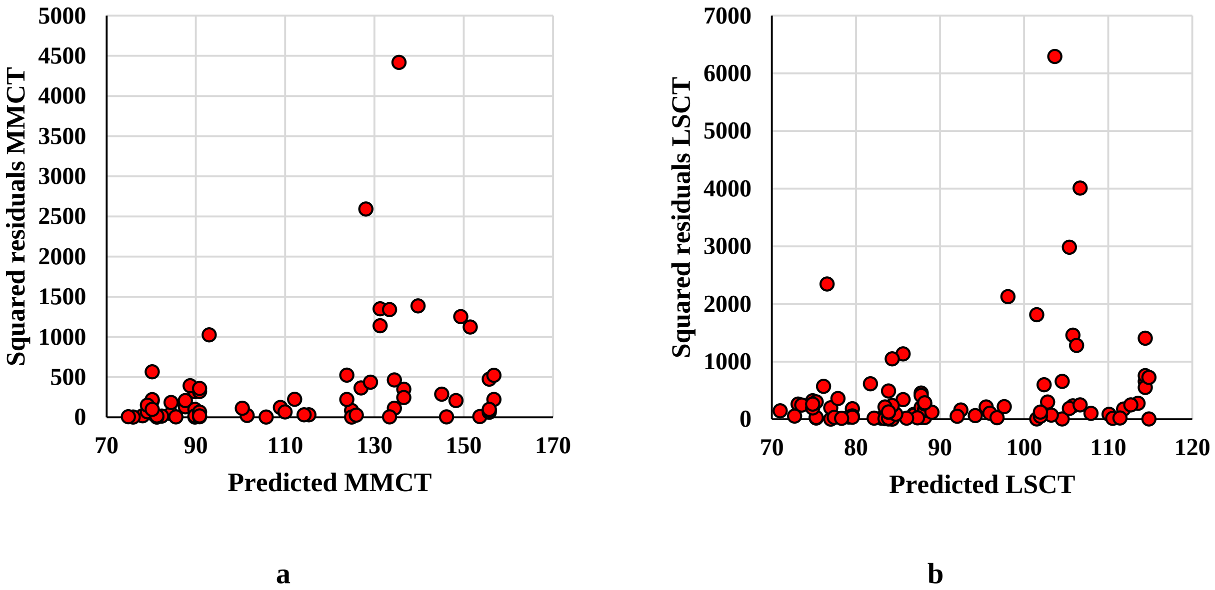


Figure A3. Results of testing for homoskedasticity: a – plot of squared residuals against the predicted manual measurement work cycle time (MMCT), b – plot of squared residuals against the predicted phone scanning work cycle time (LSCT). Note: heteroskedasticity of data was present in the model of MMCT by the results to Breusch-Pagan test ($\alpha = 0.05$, $p < 0.05$)

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