Bulletin of the *Transilvania* University of Brasov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 15(64) No. 2 – 2022
https://doi.org/10.31926/but.fwiafe.2022.15.64.2.2

MODELLING PRODUCTIVITY IN EXTRACTION OPERATIONS BY SIMULATIONS BASED ON GNSS DOCUMENTED DATA: AN EXAMPLE FROM SKIDDING TEAK WOOD IN THAILAND

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Abstract: *In Thailand, teak harvesting always includes skidding of tree length stems from landing to log yard for further processing. When terrain does not set limitations for the machines to be used, skidding is carried out by farm tractors. In this study, data was collected from 10 work cycles of teak extraction to simulate productivity of farm tractors. The GNSS data as speed and locations was used to extract operational distances and time consumption, as well as to support productivity simulation. For this, detailed measurements were done on the extracted stems to collect their diameters and lengths. For approximately six stems per load, the mean load size was 1.723 m^3. The study found that mean productivity was 17.4 m^3/h during the survey, where the mean extraction distance was 217 m. Our simulation presents productivity diagrams in relation to skidding distance. By simulation, we detected that reducing the full operational speed by 1 km/h, would decrease productivity by 1 m^3/h, when the extraction distance is less than 100 m. Another observation was that even small reductions of load sizes have a remarkable effect on productivity in short distances. Until large scale studies are to be done to evaluate the productivity in relation to variations in load size and extraction distance, the results shown herein could stand as a basis for productivity assessments.*

Key words: *teak, stems, transport, processing area, farm tractor, speed, time consumption, productivity, factors, simulation.*

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1. Introduction

One of the important tree species cultivated in Thailand to support wood production is the teak (*Tectona grandis* L.f.), whose extension was an effect of the logging ban of natural forest which has been in effect since 1989. Teak is used in the manufacture of indoor flooring, countertops, outdoor furniture, boat decks, and as a veneer for indoor finishing. It is estimated that teak plantations cover nearly 100,000 ha in the country, while the average size of a plantation is of 738 ha; plantation size ranges from 17 to 3087 ha [9]. During the establishment of new teak forest plantations, the most common spacing used in practice is 4 × 4 m (about 625 trees ha^{-1}). Management of teak plantations includes the establishment and nurturing, first thinning at 15 years, second thinning at 25 years, and clear-cutting at 30-40 years, a point at which the remaining overall tree density is 200-300 ha^{-1}. At the first thinning is common to have average DBH between 19.0-25.5 cm, while at the second thinning DBH ranges between 25.5-28.5 cm. At the clear-cutting age, the average tree size may reach at 0.50 m^3/tree [20, 21]. Teak is the most valuable tropical timber species planted in Thailand based on total area and price per solid cubic meter which, depending on log diameter, can vary from tens to several hundred Euros.

With some exceptions, the teak harvesting in Thailand is commonly done by the tree length method (*TL*) and semi-mechanized harvesting systems [16]. The cut to length (*CTL*) can be used in thinning, where for the extraction of small logs one can use manpower, mule, or log chutes [15]. The *TL* method includes basic manual work, where felling, delimbing, and toping, are the motor-manual activities done in harvesting area; these may be performed at productivities of 30 m^3/PMH, where the stem volume is 0.86 m^3 and the harvesting stock is 130-170 m^3/ha [19]. The felled stems are extracted and placed in bundles at the landing area. Then the stems are skidded to a processing area by a farm tractor, skidder, or elephant, depending on slope limitations and available resources. Study of Rianthakool [19] found productivities of farm tractors in the range of 10-25 m^3/PMH, for skidders in the range of 15-20 m^3/PMH, and for elephants in the range of 5-10m^3/PMH, when the average skidding distances were 344, 1066, and 165 m, respectively. The work procedures at the processing areas (log yards) include the following: stems are measured and graded, cross cutting points are marked, length of logs are written to stems, cross cutting is done by chainsaws, then the logs are classified and marked with identification codes [14]. The loading of vehicles for short-distance transportation is performed with self-loading two axle trucks. The purpose of the above-described procedures implemented at the processing areas is to gain a maximum yield of high value teak logs, when they are sold in auction at a long terminal. Moreover, there is less space in the forest, at the landing or at the log terminals to enable a careful measurement and grading of the logs.

Moving teak stems from landing to the processing areas is typically done by farm tractors fitted with a logging arch, to which stems or groups of stems are attached by cables. The arch is assembled to a 3-point hitch, which can raise the log ends from ground and lower them after skidding is done. The farm tractor extraction is the dominant method in flat and moderate slope terrain in Thailand. Skidders and elephants are used in mountainous areas, where slope inclination restricts the use of farm tractors. In flat terrains, the reason for using this kind of equipment is to prevent time losses incurred by operating a winch or a crane to attack/detach or load/unload the stems, making it a suitable option for short distance stem transportation. The international literature is relatively abundant in studies on farm tractor use in conventional timber extraction, which one may consider as references to estimate the time consumption and productivity for similar transportation processes. The logging arch has been described as a relatively common equipment of farm tractors in skidding operations in previous decades in the Mediterranean area and in developing countries [22]. Key findings of previous studies were that the load size was bigger, the driving speed was faster, there were less breakdowns and hang-ups, and less soil damages when operating with a logging arch. Several productivity studies were done on farm tractors equipped with a winch, where skidding distance, slope inclination, and load volume affected greatly the productivity [10, 12]. On short distances, the farm tractor skidding productivity (6.24 m^3/h) can easily compete hauling by a farm (2.80 m^3/h) or a forest tractor (5.25 m^3/h), where the average distance was 100 m uphill and slope ranged between 20 and 40% on skid trail [18]. Productivity studies on tractors equipped with a logging arch were not published during the last three decades.

Teak forest plantations require scientific support for decision making, including that in the form of predictive models, mainly because there is limited research on operational performance [1, 11] which in turn affects other important management processes such as cost estimation, operational optimization and timing. These models may be developed either by running resource intensive time studies, which should cover the variation in operational conditions, or by using highly detailed data provided by state-of-art technologies, with the aim to simulate the effect of operational conditions on the variation in time consumption and productivity. At the end of rotation, clear cutting is implemented to extract the timber which typically holds a high value. At least for this silvicultural step, data is required for a proper planning of operations with the aim to prevent resource losses. Additionally, there are several contrasting operational conditions that may affect the outcomes of estimations based on existing studies of timber extraction. As examples, there are differences in tree species, tree size, ground condition and slope, to name just few factors. In the light at the above-mentioned situation, it is important to study stem transportation from landing to processing areas under the operational circumstances of Thai teak plantations, where this operation is done in relatively flat terrains, mostly in dry conditions, and probably at higher speeds.

The aim of this study was to predict the productivity of stem extraction operations by a farm tractor fitted with a logging arch by considering the most relevant operational factors such as the extraction and maneuvering distances. The objectives of the study were set to:

i) modeling the productivity as a function of extraction distance for a dataset collected in typical conditions, *ii)* assessing the uncertainty in the productivity estimates, and *iii)* simulating the productivity by considering reasonable variations in some operational factors such as the maneuvering distance.

2. Materials and Methods

2.1. Data Sourcing

Field data supporting this study was collected on 18th of November 2022, in the proximity of a teak (*Tectona grandis* L.f.) plantation located at approximately 14°10'58.8"N – 98°55'34.3"E, at an elevation of ca. 200 m a.s.l. [8]. During the field data collection, the weather was warm and moist, and the sky was mostly clear. The plantation taken into study is managed by the state-owned enterprise, Forest Industry Organization (FIO). Currently, the company manages a teak forest accounting for an area of 78,251 ha. Typically, they run the harvesting operations from March to October, when the weather conditions are favorable. There is common to have fluctuations in the exact time and duration of the harvesting seasons between years. Harvesting season begins after high-risk forest fire season ends in January to February, and it continues until the annual cutting plan has been fulfilled, which happens in October or November. The rainy season is from June to September, when the harvesting intensity is lower.

The age of the trees harvested by clear cutting was of 30 years, and they were extracted from the compartment no. 2528, which was characterized by a spacing of 4 × 4 m, a standing stock of 1890 m^3, and an average tree size of 0.45 m^3/tree. In the compartment taken into study, thinning operations were implemented at ages of 15 and 25 years, respectively. Prior to field data collection, the trees were motor-manually felled, delimbed and topped, and the resulting stems were extracted and placed at landing in bunches. Stems forming the bunches were moved from the landing to the processing area on dirt roads, which were dry, relatively flat and in a good trafficability condition.

Although the stems were extracted from the harvesting area to the landing, which is a typical extraction operation, we refer hereafter to the transport from the landing to the stem processing area as extraction since transportation operations are required further to deliver the logs to a terminal and from there to the customers. Extraction operation was monitored for a number of 10 work cycles (turns), during which a number of 63 stems were delivered to the processing area. A Kubota M9540 four-wheel drive tractor equipped with a stem attaching and lifting device, which resembles to a given extent a logging arch (Figure 1c, d), was used to extract the stems. The machine was powered by a Kubota V3800-DI-T, 3.8 L engine outputting a nominal power of 70.8 kW. The driver had a working experience of 4 years on the machine taken into study.

Organization of work was relatively simple. The work elements observed in the field were the following:

- Empty turn, which started right after placing the GPS unit on the tractor (1 case) or after detaching the load from the tractor, and ended once the tractor arrived at the landing and engaged in positioning maneuvers; empty turn was done on dirt roads;

- Maneuver, which started right after the tractor arrived at the landing and ended once the tractor was placed in the right position for stem attachment; maneuvers consisted of movements back and forth on certain distances to place the tractor in the right position for stem attaching as well as movements to relocate or group some stems at the landing;
- Load attachment, which started once the tractor arrived to the right location to attach the stems; it consisted of hooking the stems and connecting the cables to the logging arch;
- Loaded turn, which started right after load attachment, and ended once the tractor arrived at the processing area. With one exception, loaded turn was done on the same dirt roads used for empty turn;
- Load detachment, which started once the tractor arrived at the stem processing area, and which consisted of lowering the device used to attach the cables, exiting the cabin, detaching the stems, retrieving the cables when the case, and returning to the tractor's cabin.

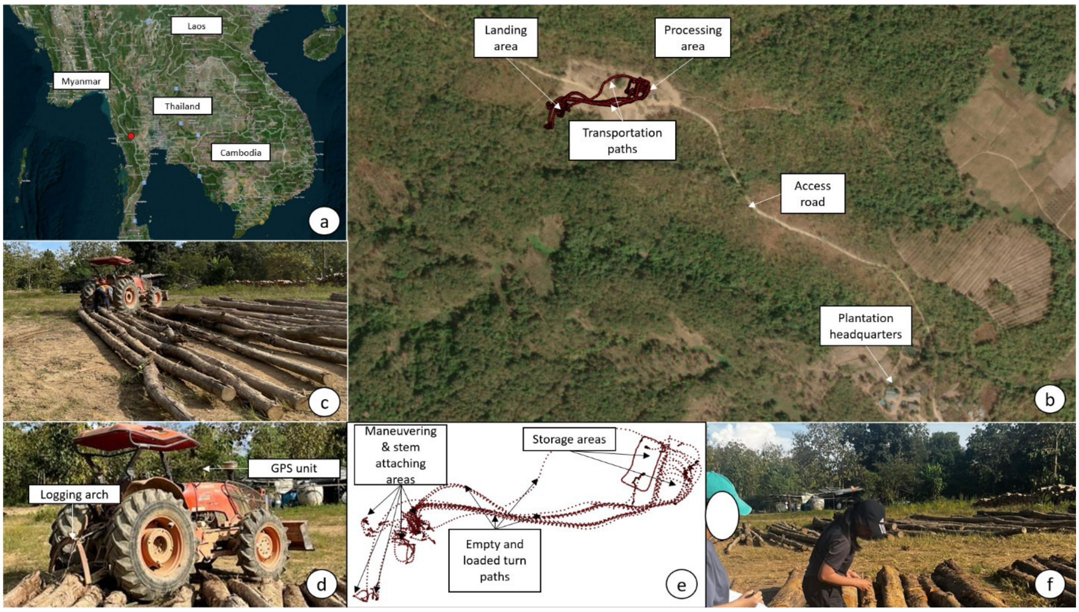


Fig. 1. *Description of the study area and of the main procedures used to collect data: a – study location at the national level (red dot stands for study location), b – detailed view of the study location, c – detaching stems at the processing area, d – placement place of the GPS unit and the equipment used to attach, lift and detach the logs (similar to a logging arch), e – details on the areas and tracks collected via GPS, f – a snapshot of measurement taken over the transported stems. Note: maps from panels (a) and (b) were built in QGis based on field collected GNSS locations and Bing® aerial and aerial labeled data, respectively; map from panel (e) was built in QGis based on field collected GNSS locations*

A Garmin® GPSMAP 64sx GPS unit was placed on the tractor in the front part (Figure 1d) and set to collect data at a rate of one second with the aim to get location and speed data (Figure 1e) to be used in productivity simulations. No important delays were observed during the collection of GPS data. However, there were two instances in which the tractor was used at the processing area to clear the ground of small logs which resulted from the ends of the stems after processing them in an adjacent area. GPS locations corresponding to these events, as well as those corresponding to placing and taking down the GPS unit from the tractor were removed from the GPS speed data set used for simulation. The stems from each load were manually measured by a forestry tape and a caliper so as to get their length and mid diameter which were used as primary data to estimate their volume as well as the volume of each extracted load. Diameters at the two ends of each stem were measured and documented as well. Diameter and length data was noted on a field book (Figure 1f), then it was moved into a Microsoft® Excel file, where the volume estimates were produced based on the Huber's formula. No processing work was done on the stems during the operations; also, stem measurements were done at the end of GPS data collection, so as not to interfere with the extraction operations.

2.2. Data Processing

Based on the field measurements done on stems' diameters and lengths, the volume of each stem (*SV,* m^3 over-bark) was estimated by the use of Huber's formula. The sum of individual stems' volumes making a load was the volume of that load (*LV,* m^3 over-bark). Along with the stem and load volumes, stem length (*SL,* m) and diameters at the middle (*Dm,* cm) and at the ends (*Dt* and *DT,* cm) were used to characterize the inputs of the extraction operation.

Location data was exported from the GPS unit in the form of a GPX file which was loaded in Garmin® Base Camp® software with the main aim of extracting data on speed to be analyzed in Microsoft® Excel®. Data extraction and processing procedures used to get the speed data in the form of numbers were similar to those reported by [2, 3, 6]. The recorded GPS track was analyzed in the software's running mode to detect the events observed in the field. Once these events were detected, their starting and ending points were noted and their data points were coded by meaningful text in a Microsoft® Excel® worksheet, and the resulted data set served as the input data to extract the time consumption, operational speed and distances. To this end, subsets of data sharing the same code were separated to resemble the succession of work elements in a typical work cycle, and the time consumption of each work element was accounted as the sum of GPS recordings of that element in a work cycle. Then, the measurement functionalities of Garmin® BaseCamp® software were used to measure the cycle wise empty (*ETD,* m) and loaded turn (*LTD,* m) distances. Figure 2 shows the variation in GPS speed plotted against the cumulated distance, and indicates the succession of work cycles and their elements.

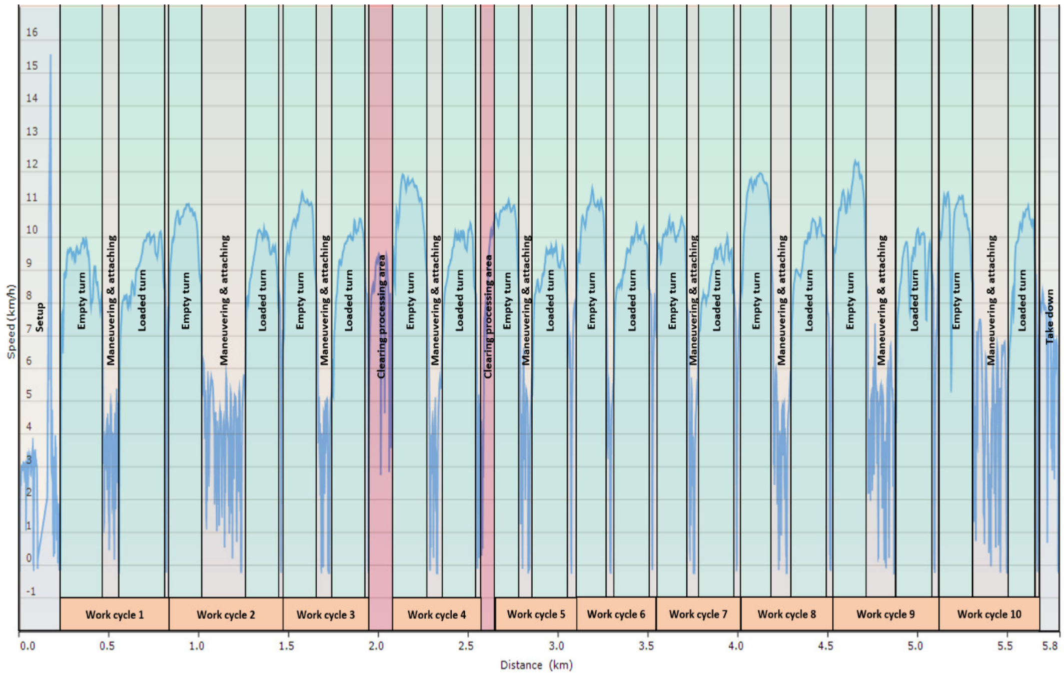


Fig. 2. *GPS speed data plotted against the main events observed in the studied work cycles. Note: setup stands for moving the machine and stopping it at a location which was used to place the GPS unit; take down stands for moving the machine at a location which was used to take down the GPS unit; load detachment took shorter periods of time within the work cycles (labels not visible in the figure). Source: figure prepared based on the coded data and speed plotted against cumulated distance as produced by Garmin® BaseCamp®*

Speed was extracted for all the work elements that supposed movement of the machine, namely empty and loaded turns, maneuvering, and clearing the processing area; similar procedures were used for those work elements which did not included movement, namely load attachment and load detachment. Speed data was saved as new data sets sharing the same code, therefore at the elemental level. By analyzing the GPS data, it was observed that at the beginning and ending of empty and loaded turns, there were increasing and decreasing trends in speed data. This was related to the time needed to change gears so as to be able to operate the machine at the intended operational speed. To prepare speed data of these elements for simulation, their corresponding data sets were checked, and the first and last 10 observations were extracted and moved in two new speed data subsets. Accordingly, for simulation purposes, the speed of empty and loaded turns considered these sub-events and was divided in regular operational speed, named hereafter “full speed”, and the “entry-exit” speed of the empty and loaded turns, respectively. This kind of decomposition was necessary for productivity simulation outside the range of collected data, therefore for lower and higher extraction distances, where the studied machine is expected to return different shares of these two speed categories.

2.3. Statistical Analysis and Software Used

Statistical analysis was implemented by a set of simple descriptive steps. Since the volume of the loads was an important parameter to characterize productivity by simulation, the variables characterizing the stems within the studied loads were checked for normality, and descriptive statistics were developed to characterize their central tendency and dispersion. Assumption of normality in data was tested by the Shapiro-Wilk test, and the computed descriptive indicators were the minimum, maximum, mean, median and standard deviation values. In particular, assumption of normality in data was useful to choose the best descriptive metric to be used in productivity simulation, since the simulation had to be based on either the mean or median load volume; checking for normality in data was done at a confidence level of 95% (α=0.05, $p<0.05$). Time consumption and operational distances (empty and loaded turn distances) were statistically analyzed by the same steps. However, the time study data was not used for modeling purposes, but to compare with the results of simulation in terms of speed. For that reason, in addition to the descriptive statistics described above, elemental time study data was characterized also by the coefficient of variation. Speeds during the events which involved movement were important parameters for simulation. Once the data was organized on events, the steps of descriptive statistics and checking for normality described above were implemented also for GPS speed data. Statistical analysis was done with the support provided by the Real Statistics add-in, which is a freeware tool that extends significantly the capabilities of Microsoft® Excel® in running statistical analyses. A copy was downloaded from https://www.real-statistics.com/ [13] and used in this study for statistical steps such as checking for normality in data and building boxplots for descriptive statistics. The rest of data processing steps, including organization of data, simulation and producing artwork were supported by Microsoft® Excel®.

2.4. Simulation

Simulation part of the study took the approach of examining the effect of changing operational conditions in terms of extraction, entry-exit and maneuvering distances over the expected productivity for the extraction operation taken into study. The GPS speed was assumed to be close to the real, operational speed. For details on the accuracy of the used GPS, as well as of GPS measurements in forest operations one may check the work of Borz et al. [2] and Keefe at al. [17]. Based on our experience, the use of handheld GPS units in forest operations was able to provide useful information for dedicated studies [2, 3, 5]. Average speeds returned by the statistical analysis for entry-exit (*EES,* km/h), maneuvering (*MS,* km/h), empty (*ETS,* km/h) and loaded (*LTS,* km/h) turn events were used as a baseline to plot productivity against the extraction distance, which was considered to be the most relevant factor affecting productivity. To this end, productivity (*P,* m^3 over-bark/h) was estimated based on the mean load volume (*LV,* m^3 over-bark) holding as a measure of uncertainty its standard deviation (*LV±LVSD,* m^3 over-bark) to account for the upper and lower limits of productivity one may get due to standard uncertainty based on the simulated data. This approach led to a bivariate plot showing the variation in productivity and its uncertainty for the studied conditions, which were extrapolated to extraction distances between 10 to 1000 m, by a step *i* of 10 m. The extraction distance used in simulations was assumed to be assimilable to the arithmetic mean of the empty and loaded turn distances. Based on the extraction, entry-exit and maneuvering distances, work cycle time was computed using Eq. (1), with the support of Eqs. (2)-(7).

$$WCT_i = ET_i + MT_i + AT_i + LT_i + DT_i + EET_i \quad (1)$$

$$ET_i = \frac{ED_i}{ETS} \cdot 0.278 \quad (2)$$

$$MT_i = \frac{MD_i}{MS} \cdot 0.278 \quad (3)$$

$$AT_i = 79.2 \quad (4)$$

$$LT_i = \frac{ED_i}{LTS} \cdot 0.278 \quad (5)$$

$$DT_i = 31.6 \quad (6)$$

$$EET_i = \frac{EED_i}{EES} \cdot 0.278 \quad (7)$$

$$P_i = \frac{LV}{WCT_i} \quad (8)$$

$$PU_i = LV + \frac{LVSD}{WCT_i} \quad (9)$$

$$PL_i = LV - \frac{LVSD}{WCT_i} \quad (10)$$

where:

subscript *i* stands for the current distance step considered in simulation;

WCT – the work cycle time (seconds) computed based on Eqs. (2)-(8) which was converted in hours for using it in Eqs. (8)-(10);

ET – the empty turn time [s],

ED – the simulated extraction distance [m];

ETS – the average speed during empty turn at full speed [km/h];

0.278 – the conversion factor between speed expressed in km/h and speed expressed in m/s;

MT – the maneuvering time [s];

MD – the average (or simulated) maneuvering distance [m];

MS – the average speed during maneuvering [km/h];

AT – the load attaching time, mean value used in simulation [s];

LT – the loaded turn time [s];

LTS – the average speed during loaded turn at full speed [km/h];

DT – the load detaching time mean value used in simulation [s];
EET – the entry-exit time [s];
EED – the average (or simulated) entry-exit distance [m];
EES – the average speed during entry-exit events of the empty and loaded turns [km/h];
P – the productivity estimate [m^3 over-bark/h];
LV – the mean load volume [m^3 over-bark];
PU – the upper limit of productivity estimates [m^3 over-bark/h];
LVSD – the standard deviation of load volume [m^3 over-bark/h];
PL – the lower limit of productivity estimates [m^3 over-bark/h].

In a next step, the entry-exit and maneuvering distances were the factors which were altered by considering practical reasons. For instance, maneuvering distance could vary quite widely depending on the location of stem bunches. Entry-exit distance could also vary quite widely depending on the configuration of landing and processing areas, respectively. To simulate the effects brought by the variation in these distances, maneuvering distance was tuned by considering values of 10, 20 (which were close to the average of the data observed in the field) and 50 m, respectively. Then, for each maneuvering distance, the entry-exit distance was tuned by considering the same values, where an average value of up to 10 m was close to the conditions of this study. This design resulted in nine simulations of productivity as a function of extraction, maneuvering and entry-exit distances.

3. Results and Discussion
3.1. Description of Data

In total, 63 stems were extracted during the field study, which accounted for a number of 10 loads (Table 1).

Descriptive statistics of stems and loads Table 1

Variable (abbreviation and measurement unit)	Descriptive statistics					
	No. of observations	Minimum value	Maximum value	Mean value	Median value	Standard deviation
Stem length, *SL* [m]	63	3.25	14.48	9.08	8.76	2.49
Diameter at the thin end, *Dt* [cm]	63	10.60	26.00	16.15	16.10	3.48
Diameter at the thick end, *DT* [cm]	63	16.90	39.30	27.18	26.80	5.81
Diameter at the middle, *Dm* [cm]	63	12.20	27.40	19.25	19.30	3.44
Stem volume, *SV* [m^3 over-bark]	63	0.072	0.577	0.273	0.260	0.122
Load volume, *LV* [m^3 over-bark]	10	0.953	2.308	1.723	1.826	0.430

Note: assumption of normality was met for all variables.

Stem length varied from ca. 3 to ca. 15 m, averaging approximately 9 m. Estimations of stem volume ranged from 0.07 to 0.58 m^3 over bark, averaging 0.27 m^3 over bark. Load volume was found to range between approximately 1 and 2.3 m^3 over bark, averaging ca. 1.72 m^3 over bark. Following the statistical tests, it was found that normality assumption was met for all the variables reported in Table 1. Accordingly, the productivity simulations were carried out by considering the mean volume of the load.

Descriptive statistics of operational variables and time consumption Table 2

Variable (abbreviation and measurement unit)	Descriptive statistics						
	No. of observations	Minimum value	Maximum value	Mean value	Median value	Standard deviation	Coefficient of variation
Number of stems per load, *NS* *	10	4	9	6.3	6	0.43	27
Load volume, *LV* [m^3 over-bark] *	10	0.953	2.308	1.723	1.826	0.430	25
Empty turn distance, *ETD* [m]	10	203	244	213.4	210	11.72	5
Loaded turn distance, *LTD* [m]	10	138	260	220.8	226.5	31.64	14
Empty turn time, *ET* [s]	10	73	104	81.8	81.5	8.55	10
Maneuver time, *MT* [s]*	10	12	213	104.5	89	69.50	67
Load attaching time, *AT* [s]*	10	35	157	79.2	62.5	42.58	54
Loaded turn time, *LT* [s]*	10	70	112	98.2	99.5	11.70	12
Load detachment time, *DT* [s]	10	20	66	31.6	24	16.11	51
Other time categories, *OT* [s]*	3	52	157	90.33	62	57.95	64

Note: *assumption of normality was met for these variables.

Table 2 reports the main descriptive statistics of operational variables and time consumption. Only part of the variables, including the number of logs per load, met the assumption of normality in data. Empty and loaded turn elements accounted, on average, for a time consumption which was proportional to their corresponding distances. However, there was a slight difference in operational speed, which was of 2.57 and 2.27 m/s for the empty and loaded turns, respectively. Roughly, these accounted in the original dataset for speeds of 9.4 and 8.1 km/h, respectively. Load detachment time accounted, on average, for less than half of the load attachment time. Maneuvering time, which was characteristic to the study conditions, accounted for approximately 1.5 minutes. The last time consumption category from Table 2 stands for clearing the processing area and other events such as taking down the GPS unit from the machine, and it was not included in simulation.

Based on the data shown in Tables 1 and 2, as well as on the data supporting these statistics, the mean extraction distance was of approximately 217 m, ranging from 178 to 252 m. Maneuvering distance approached, on average, 15 m and the entry-exit distances averaged less than 10 m. The operated volume was estimated at ca. 25 m^3 over-bark, and the total time needed to operate it was of 1.437 hours. In an approximated estimation, this would mean a productivity of 17.4 m^3/h.

Figure 3 shows the descriptive statistics of the event-related operational speeds. Empty and loaded turns accounted for most of the GPS collected data, while maneuvering was found to be the most frequent event in the data set. Based on the recorded GPS data, empty turn speed was found to be the highest, accounting, on average, for 9.42 km/h. Next in line was the speed during the loaded turn, which accounted for 8.24 km/h. Maneuvering was done at an average speed of 2.93 km/h, while load attachment-detachment events were characterized by speeds close to 0 km/h.

There were, however, important variations in event-based speeds. Empty and loaded turns, for instance, outputted speeds in the range of ca 1 and 12 - 11 km/h, respectively. This was due to those events covering the first seconds of machine driving, in which the speed either increased up to the full speed or decreased to a full stop. Speed data characterizing the event-based dataset was found to fail the normality test. However, the median and mean values were close in magnitude. For instance, the median value of empty turn speed was of 10 km/h while the median value of the loaded turn speed was of 9 km/h. For maneuvering, the median value of speed was of 3 km/h, which was close to the mean value of 2.93 km/h.

Following the decomposition of speed data on sub-events, the descriptive statistics of the data sets changed significantly.

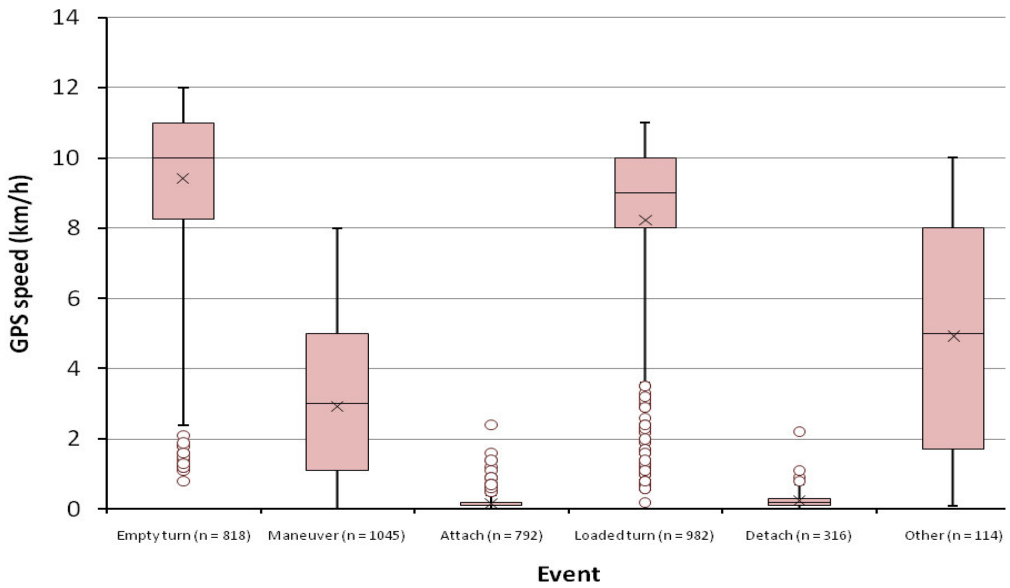
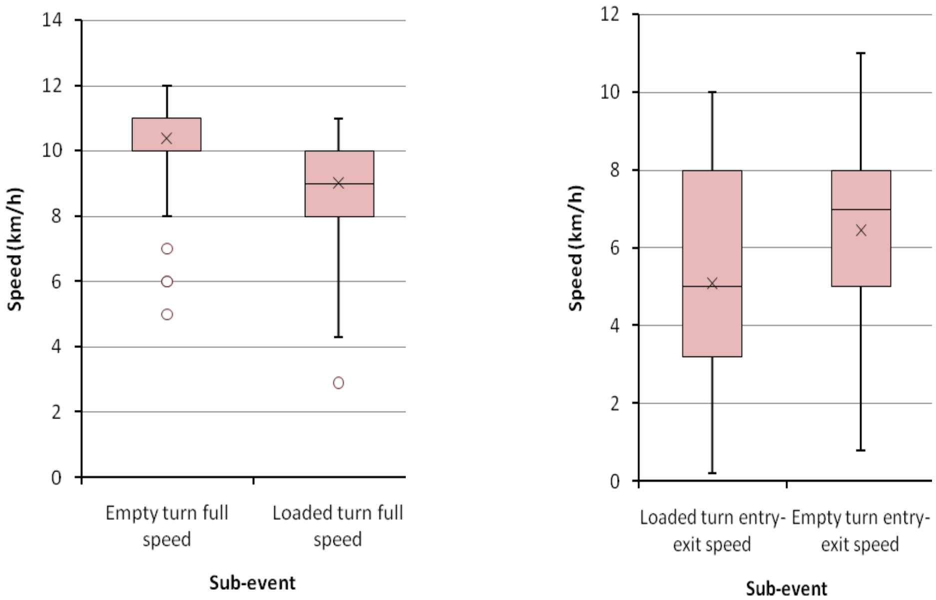


Fig. 3. *Descriptive statistics of event-related speeds. Note: circles stand for outliers as computed by the Boxplot functionalities in Real Statistics, "×" stand for the mean values, rectangles stand for interquartile ranges, and horizontal lines located near the center of the rectangles stand for the median values*

Figure 4 reports the descriptive statistics of the empty and loaded turn speeds by accounting for the full operational speed and entry-exit speeds. The mean values of full speeds increased by approximately 1 km/h in both cases (Figure 4a) as opposed to the mean values of the original datasets (Figure 2). Also, there was less variability in data, which is shown by the shortened normal and interquartile ranges and the reduced number of outliers. A similar description applies to the data shown in Figure 4b, where the entry-exit speeds of empty and loaded turns indicate lower values, although there were found to vary in wider ranges, which was specific to data segments identified for these subsets. These events were, on average, slower for the loaded turn as compared to the empty turn.

In numbers, the mean values of empty and loaded turns at full speed were of 10.38 and 9.04 km/h (median values of 11 and 9 km/h), respectively. Their corresponding entry-exiting events ran at average speeds of 6.46 and 5.11 km/h (median values of 7 and 5 km/h), respectively. All of the speed data sets taken into analysis failed the normality assumption.



a **b**

Fig. 4. *Descriptive statistics of empty and loaded turn speed data following its decomposition on sub-events. Note: circles stand for outliers as computed by the Boxplot functionalities in Real Statistics, "×" stand for the mean values, rectangles stand for interquartile ranges, and horizontal lines located near the center of the rectangles stand for the median values, excepting the "empty turn full speed" from panel a, where the upper part of the rectangle stands for the median value. Number of observations in "empty turn full speed", "loaded turn full speed", "loaded turn entry-exit speed" and "empty turn entry-exit sped" were of 618, 782, 200 and 200, respectively*

3.2. Simulation

Since the differences between the mean and median values were small in all the speed data sets, simulations were based on the mean values. Accordingly, values of 10.38, 9.04, 6.46, 5.11 and 2.93 km/h were used for the full speed empty, full speed loaded, empty entry-exit, loaded entry-exit and maneuvering events when computing the simulated work cycle times. These were complemented by the use of average time consumption of attaching and detaching events, and the mean value of the load with its standard deviation, as shown in Eqs. (1)-(8). Figure 5 shows the results of simulation. Figure 5a shows the results of simulation by considering the range of extraction distances from 10 to 1000 m, as well as distance conditions for the maneuvering (10 m) and entry-exit events (10 m), which were close to those supporting the data of this study.

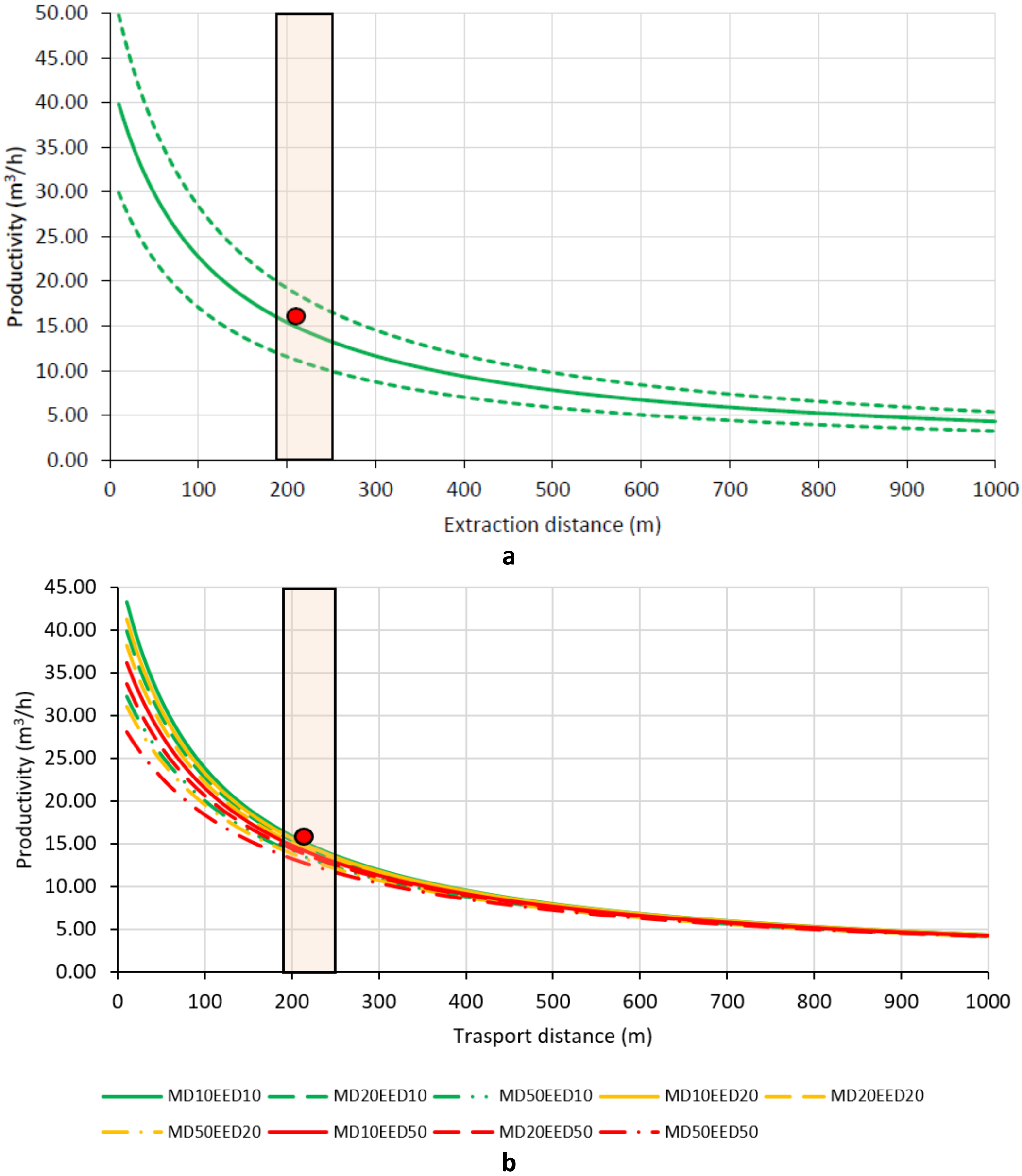


Fig. 5. *Simulated productivity against the extraction distance. Legend: a – productivity (continuous line) simulated as a function of extraction distance including standardized uncertainty (dashed lines), b – productivity simulated as a function of extraction distance and distances selected for maneuvering (MD) and entry-exit (EED) events. Note: Red dots stand for the average productivity based on the time study data and rectangles stand for the range of extraction distances covered by this study. Numbers in the legend stand for the values of distances (e.g. MD10EED10 stands for a maneuvering distance of 10 m and an entry-exit distance of 10 m)*

As shown in Figure 5a, standardized uncertainty was higher in magnitude for lower ranges of extraction distances. As an example, for extraction distances of 100 m, one may find uncertainties in productivity accounting for ±5 m^3/h. This was due to a higher effect that variation in load size may bring in lower ranges of extraction distances. The simulated productivity decreased sharply as a function of extraction distance. As it decreased, so did the standardized uncertainty, which for a distance of 500 m was reduced to about ±2.5 m^3/h. In the range covered by the data supporting this study, the simulated productivity was close to that estimated from the time study data. There were some differences (up to 2m^3/h) due to an inexact matching of the distances selected for maneuvering and entry-exit events, as well as due to the speed's descriptive statistic used to simulate the productivity; however, the variation of these distances in the selected range seemed to add a small if no effect in productivity for extraction distances exceeding 500 m. Their effect was important in a range of extraction distances which were up to those observed in this study. For instance, at an extraction distance of 100 m, and entry-exit distances of 10 m, maneuvering distance can significantly affect the productivity (green lines, Figure 5b). Taking as a reference a maneuvering distance of 10 m, if such maneuvers are to be done on 50 m, this will mean a drop in productivity of ca. 4 m^3/h. As opposed, for a maneuvering distance of 10 m, increasing the entry-exit distances from 10 (green continuous line) to 50 (red continuous line) m, would have less effect on productivity (drop of up to 4 m^3/h). Accordingly, by excluding the effect of the extraction distance, the best scenario for productivity would be that in which the bunches of stems are close together, enabling maneuvers on short distances, while the entry-exit distances are short and travelled on good ground. To these, however, one needs to add the uncertainty brought by the variation in load size.

3.3. Discussion

This study is based on measurements of load volume and operational speed, which were used to simulate productivity of the studied operation as a function of the extraction distance. First point to be addressed is that related to the estimates of stem volumes since these were used to calculate the volume of loads and to estimate the mean load volume. Our estimates are based on the use of Huber's formula. However, we feel that these are somehow conservative since the stems had rather large buttresses at one end. As such, the reported statistics on payload volume and productivity could be seen as conservative. There were attempts to estimate the volumes by the Smalian's formula (not shown herein), but the differences found were large enough to be considered as over-estimations. In fact, there are no perfect methods of volume estimation, particularly when dealing with broadleaves and tapers that not fit well to cylinders. For instance, keeping the distances of maneuvering and entry-exiting close to those of this study, a shift of 0.1 m^3 in the mean load size would lead to increasing the productivity by 1.4, 0.9, and 0.5 m^3/h at extraction distances of 100, 217 and 500 m, respectively. While there were no feasible solutions to estimate the volume of the stems at the time of collecting the data, such solutions, including digital ones, are currently being researched [4, 7], and they will most probably lead to better methods of estimation.

GPS speed extracted from handheld units has been proved to be useful in many applications of forest engineering [2, 3, 5, 17]. In this study, it was used for simulation, based on the average values returned by a detailed analysis of the observed events. Similar to the load volume, changes in operational speed could affect the outcomes of simulations presented herein. From this point of view, the first thing to think about is whether the speed as recorded in the observed events would be kept the same in other field operations. Then, the study was based on a limited range of distances, in which the operator was doing his job at a given speed, leaving some uncertainty in relation to what would happen in his operational speed behavior if the extraction distances would be higher. To address the first point, a drop of 1 km/h in the "full speed" of empty and loaded turns would produce drops in productivity of up to 1 m^3/h. However, the law of differences in productivity would probably have a different shape as opposed to that brought by changes in the load volume. Although not shown herein, we simulated a drop in full speed of empty and loaded turns of 1 km/h. This led to a sharp decrease of productivity in the range of extraction distances from 10 to 100 m, followed by a moderate increase of productivity from that point on up to 1000 m. However, the difference at 1000 m was still negative, accounting for 0.25 m^3/h. The magnitude of productivity loss would be, however, affected by the magnitude in speed. At half speed of the empty and loaded turns used for simulation in this study, in lower ranges of extraction distances the drops of productivity will be sharp, accounting for almost 5.5m^3/h at a distance of 100 m. By the same law, the drops of productivity would attenuate as the distance would increase, ending at a loss of ca. 1.5 m^3/h for a distance of 1000 m. This naturally leads to discussing what could be the factors that could effectively lead to drops in speed. Assuming the same type of roads used for extraction, changes in their condition, particularly in moisture, would probably lead to a decrease of operational speed. This would be due to loosing adherence and grip causing slipping in wet terrains. The second point is related to the changing behavior in operations. By the distances covered in this study, and by assuming similar operating conditions, it is likely that the operating speed would be similar. Eventual variations, would lead to only small changes in productivity, as proved by the examples given above.

Speed that can be sustained during the operations is a factor of first importance affecting the productivity. Even for machines such as forwarders, the speed was discussed [2] to generally lay between 1.6 and 5 km/h for the empty and loaded turns developed inside the forest. In a similar study of Spinelli and Baldini [22] the load volumes for silver fir accounted for 1.289-1.337 m^3, and skidding distances were 136 and 73 m, respectively. The productivities were estimated in the range of 4.509 and 5.080 m^3/h. Compared to the results of this study, this says much about the importance of having the capability to run the operations at higher speeds. Similar findings, supporting the importance of sustaining increased operational speeds were reported by Borz et al. [2], who checked if there is possible to operate a forwarder prototype at higher speeds, and if so, what effects would this bring on productivity.

There are some limitations of this study which need to be addressed. First of all, standard deviation was used as a measure of standard uncertainty in load volume and productivity estimates. This option would cover only ca. 70% of probability that new measurements will be found in the range defined by the average load and its standard deviation. Since the number of loads was small anyway, we felt that increasing this level of confidence will add no supplementary scientific value; therefore, the results of simulations need to be interpreted with caution and they are rather indicative. This leads to the second limitation, namely that of having a rather low sample as a basis for running the simulations. Future studies playing with simulation of productivity could add more value to the accuracy of the models by including more background data in them. Still, this study has the merit of proving how the GPS data can help to simulate productivity under changing operational conditions. In addition, there was less variability in data following speed decomposition on typical events, a fact which could stand as indicative for the validity of results when extrapolated to other operational conditions.

4. Conclusion

This study is based on simulation of productivity in teak stem extraction operations having as inputs the operational speed at event level and the size of the operated loads. As such, the results reported herein are sensitive to eventual changes or variations in speed and size of the loads. Nevertheless, the results could be used as a basis for operational planning until full scale studies will be implemented to address the variations in load size and speed as of different operational conditions. In particular, the approach taken in this study could be extended to larger datasets so as to build more robust statistics on speed and load to be used in further simulation. This would help in having increasingly reliable models to predict and plan the operations.

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