Comparison of Short-Wood Forwarding Systems Used in Iberia

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Spinelli, R., Owende, P.M.O., Ward, S.M. & Tornero, M. 2004. Comparison of short-wood forwarding systems used in Iberia. Silva Fennica 38(1): 85–94.

Time studies were conducted to quantify the productivity and the operational cost of mechanized wood extraction in the Iberian Eucalyptus plantations. The key objectives were: to determine the significant variables that influence machine productivity and extraction costs in shortwood transport within the forest and to find the basis for optimization of shortwood transport with respect to Eucalyptus forest stands. Three machines were selected for study, each representative of the different log forwarding regimes that are used in Iberia and that could be extended to most of Southern Europe. These were: 1) a modified articulated dumper, 2) a purpose-built forwarder and 3) a farm tractor paired to a twin-axle forestry trailer.

It was observed that the productivity and the cost of shortwood extraction may vary from 6 to 15 fresh tonnes/SMH and 3.5 to 6.5 Euro/fresh tonne, respectively. It was estimated that the optimal extraction route network covered approximately 10% of the forest surface. It was also observed that the modified dumper is the most-productive unit, and given its higher speed (>5 km/h) and larger payload (16 tonnes), it is the economic choice for extraction distances in excess of 1000 m. However, it also generates the most severe rutting, hence it should be used with caution. For extraction distances below 1000 m, the light purpose-built forwarder compares favourably with the modified dumper, while generating less than half the site disturbance. The tractor-trailer combination is economically inferior to the modified dumper and the light forwarder, and should be regarded as a complement to the main extraction fleet and where short-haul operations are required. Under the assumptions of the study, light forwarders (8-tonne payload) may become competitive with heavier ones when road density is at least 6 m/ha, so that extraction distance does not exceed 1 km. This study provides a model for estimating the productivity and the cost of timber forwarding under varying conditions.

Keywords Eucalyptus, forwarding, site disturbance, cut-to-length harvesting
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Received 21 July 2003 **Revised** 16 October 2003 **Accepted** 3 December 2003

1 Introduction

The mechanized cut-to-length (CTL) system consists of felling, delimbing and bucking trees into logs of specified lengths at the stump. Logs are then transported to a landing by a forwarder. This system offers several advantages, notably the smaller size of landing area that is required and minimal damage to the logs during handling and transport. Over the years, the system has become increasingly mechanized and it is now based on harvester and forwarder. The mechanized cut-to-length system has gained world-wide acceptance, expanding far beyond the limits of boreal forestry. When the original Nordic product cannot satisfy local needs, specific adaptations are developed. This is particularly true with the forwarder, as its design allows for more technical flexibility than the harvester does. Consequently, forwarders now operate under a variety of working environments, that are often very different from those for which the machine was originally intended. The forwarders used in Iberia handle heavier wood, and they must also cope with the inherent steeper terrain and warmer weather. As a consequence, machine performance, technical availability and the impacts on the environment may be significantly altered.

Furthermore, the socio-economic conditions of Southern European forestry are much different and more diversified than in Fennoscandia, where the harvester-forwarder system has reached a certain standardization in the way it is designed, planned and implemented (Brunberg et al. 2000). For all these reasons, a number of alternative strategies have been developed to cope with the forest and the terrain characteristics of Southern Europe.

Traditionally, Eucalyptus logs are forwarded with all-terrain trucks, often obtained from auctions of military surplus. These units can attain productivity of over 10 tonnes/scheduled machine hour (SMH) for an extraction distance of 250 m, on flat terrain with a dense network of extraction routes covering approximately 40 m/ha (Verani 2001). When harvesting on rough terrain, the need for better off-road vehicles gets urgent. Modified farm tractors are often used, but their mobility on many forest sites is limiting, hence, purpose-built forwarders are preferred. Forwarders are considered to be reliable and their productivity are in the range of 8 to over 20 tonnes/SMH, depending on the model and the working conditions (UK Forestry Commission 1998, Gullberg 1997, Martin dos Santos et al. 1995, Saunders 1996). Recent tests conducted in the Croatian floodplains have indicated that these machines can forward heavy oak logs over comparatively long distances and still obtain a productivity of about 10 m^3/SMH (Goglia et al. 1999, Horvat et al. 1999).

In Southern Europe, however, the introduction of Scandinavian-made forwarders is progressing slowly. This might be related to both the climate and the socio-economic conditions of the region. At any rate, local manufacturers in Spain have developed their own version of the forwarder, offered on the market at attractive prices. Although these machines are already obtaining the attention of the international press (Burke 2002), no studies are available on their performance. At first sight, the new forwarders produced in Spain resemble the older generations of the Nordic line, as it can be checked by comparing their respective market reviews (Åkerman 1976, Daly 2001). But of course over twenty years have elapsed, and even the same concept is no longer implemented with the same technical solution. In fact, Iberian forwarders should be regarded as a new, adapted species of the larger forwarder family.

This project was conducted as a further step towards producing an overall simulation model of harvesting options for Eucalyptus plantations. Once assembled, the final model would allow managers to compare the performance of alternative harvesting strategies under their conditions of choice. Forwarding is a key element of the cut-to-length harvesting chain and must be included in any such model. However, limited scientific knowledge is presently available on the forwarding of Eucalyptus logs under these conditions and therefore the need arose of determining the significant variables that influence the productivity and cost of shortwood transport with alternative forwarders under the conditions of these stands. Attention was also paid to the soil impact consequent to each choice, which may inform machine selection. This was not studied in detail, because that would have required a very complex study: yet an indicator was provided for comparing the relative impact of each machine choice. Rut depth was chosen as a practical indicator of soil impact (Wästerlund 1992, Wronski and Humphreys 1994).

2 Materials and Methods

2.1 Description of the Study Site

The study was carried in a 54 ha, even-aged Eucalyptus stand at Finca de Villabona, in Northern Spain. The forest on a hillside was planned for clear-cut harvesting at the age of 14. The terrain slope was moderate (avg. 23%), with maximum gradients of up to 40% on some areas. The general stand and terrain characteristics are presented in Table 1.

The logs to be extracted had been debarked and cut into 2 m lengths, and stacked within the forest stand. Log processing had been done mechanically, using excavator-base harvesters in 35 m spaced trails. Forwarding operations mainly used the harvester trails, but the main extraction trails were constructed after the harvesting operation. The logs were forwarded to a landing, adjacent to a public road. Each experimented forwarder was allocated a specific area for unloading, as the work was performed by contractors paid on a piece-rate basis.

Table 1. Description of the study site.

Species	*Eucalyptus globulus*
Rotation	Third
Age (years)	14
Stand density (stools/ha)	1250
Stand density (stems/ha)	1600
Type	Multi-stem
Avg. tree mass (fresh kg)	122.8
Avg. DBH (cm)	12
Avg. height (m)	18
Stocking (fresh tonne/ha)	197
Harvesting regime	Clear-cut
Average slope (%)	23
Terrain class [a)]	2.2.3 (i.e. good ground conditions, slightly even terrain, moderate slope)
Soil type	Fine-loamy brown earth

[a)] According to UK Forestry Commission 1995

2.2 Description of the Forwarders

Three machines were selected for study, each representative of a different technological solution used in Iberia. These were: 1) a modified articulated dumper, 2) a purpose-built forwarder and 3) a farm tractor paired to a twin-axle forestry trailer (Fig. 1). The technical characteristics of these machines are shown in Table 2.

The articulated dumper was modified for forestry applications by removing the tipping bin that is used for quarry work. The rear chassis was extended and fitted with headboard and bolsters, and a loading crane. The tires were of size 20.5–25 and were re-treaded with tractor lugs. Despite the increasing number of purpose-built forwarders, the modified quarry dumper still makes a popular extraction vehicle in Southern Europe. The reasons are that the dumper is much sturdier than a purpose-built forwarder: its payload is in excess of 20 tonnes and this is suitable to extracting Eucalyptus wood, which is very heavy (density in the range of 1.1 tonnes/m^3 fresh). Dumpers have a higher load index (ratio between load weight and tare weight) than purpose-built forwarders, i.e. 1.4 vs. 0.8 respectively. This limit has not been overcome yet, despite recent developments in forwarder design (Brunberg et al. 2000, Löfgren 1999). The dumper has automatic transmission, which builds up less heat than the hydrostatic type mounted on most purpose-built forwarders, which is a significant advantage in the hot climate of Southern Europe. The automatic transmission also allows for high travel speed: up to 50 $km\,h^{-1}$ may be achieved on level road. A modified dumper is cheaper to purchase than a standard Scandinavian forwarder: the specimen in the study was costed at approx. 160 000 Euro, which is about 20% less than the cost of a 10-tonne purpose-built Scandinavian forwarder.

The purpose-built forwarder used for the test was a Spanish-built light unit, designed as a compromise between the modified dumper and the large purpose-built forwarder. It represented a whole class of machines: purpose-built forwarders in all their characteristics, but simpler and cheaper than the Nordic products. Generally

Fig. 1. Machines selected for the study: modified articulated dumper (top left), a purpose-built forwarder (top right) and a farm tractor paired to a twin-axle forestry trailer (left).

equipped with mechanical transmissions, Spanish forwarders offer indeed a 'jerkier' ride than Nordic ones, but they are also faster and less likely to develop heating problems. They are certainly worth considering, as they offer a reduced-impact alternative to the modified dumper, for the attractive price of app. 100 000 Euro per unit. In fact, the high investment cost of Scandinavian forwarders represents a problem for many loggers, and not only in Spain (Cuchet 1997).

Table 2. Specifications of the forwarders.

Machine	Modified dumper	Purpose-built forwarder	Tractor-trailer system
Configuration	6 × 6 wheel drive	6 × 6 wheel drive	4 × 4 wheel drive
Weight (tonnes)	17.2	9.5	11.0
Engine	Volvo TD 73K	Deutz 913	Sisu Diesel 20
Power (kW)	187	89	81
Transmission	autom. 5 + 1	man. 5 + 1	powershift 12 + 12
Max. speed (kmh)	52	30	40
Width (mm)	2490	2500	2100
Length (mm)	9675	8093	8500
Height (mm)	3225	3500	3200
Ground clearance (mm)	460	400	400
Payload (tonnes)	22.5	8.5	8.0
Loader	Loglift 61F	Guerra 624	Guerra 55T
Approximate price (Euro)	160 000	100 000	100 000
Operator (n)	1	1	1
Operator experience (years)	8	6	5

Forwarding with farm tractors that have been modified for forwarding applications is common practice almost everywhere in Europe, including in Scandinavia, where purpose-built forwarders dominate. While the farm tractor and forestry trailer combination lacks the mobility of a purpose-built forwarder, it is versatile in that it can be used in a variety of tasks, including forwarding, skidding and loading, apart from the associated agricultural work. The unit experimented consisted of a four wheel drive farm tractor with a twin axle trailer. The tractor was fitted with all appropriate guarding, front blade and ballast. A winch had been installed on the nose of the tractor and a hydraulic loader on its rear end. The trailer had twin axle, which received power from the tractor power take-off shaft. The price of the complete unit is app. 100 000 Euro.

The machine extraction tasks were assigned on the following basis: the dumper was assigned to extracting the wood from approximately 1600 m from the landing; the farm tractor covered the scattered small patches, on easy terrain and near the road; the light forwarder would extract the rest of the wood, at times on steep terrain. The average extraction distances covered by the three units are substantially different (Table 3). All the machines were operated by experienced drivers, who had operated their respective units for a number of years and were very proficient in their use. They all had a good perspective of the logging operation as a whole, and did their best effort to correctly manage the interface with the other teams. Operators had been chosen from a larger pool for their recognized good-average skill.

2.3 Data Collection Routine

The data collection procedure consisted of a set of time studies. Cycle times for each machine were split into time elements, considered to be typical of the wood forwarding process. This was done with the intent of isolating those parts of a routine that are dependent on one or more external factors (viz. load size, travel distance, number of logs), in order to enhance the accuracy of the productivity models (Bergstrand 1991, Gullberg 1997). All time elements data were recorded using a stopwatch.

The distances covered by the machines were measured by pre-marking all the extraction routes and measuring the corresponding distances with a hip-chain. The slope of each trail was measured at 20-m intervals using a clinometer. Load size was estimated by counting the number of logs contained in each load, and applying an average log weight to the total. The average log weight was obtained by counting the number of logs on four trucks and taking each truck to a certified weighbridge. As a further reference, the stacked volume of all forwarder- and truck-loads was also measured using a metric tape. Fresh weights were used all along the study. Rut depth was measured at 20-m intervals on all trails. On each measuring point, a stick was placed on the rut walls and the depth was measured perpendicularly to the stick, with a rigid measuring tape.

The time data collected were analysed, in order to establish the significance of selected independent variables to discrete machine process cycle times. Multiple linear regression and correlation analyses were used to express the machine process time expenditures as functions of the most significant independent variables. The terms in the established relationships were tested for significance at $p < 0.01$.

3 Results and Discussion

3.1 Productivity and Cost

Machine productivity is reported both as productive machine hours excluding delays (PMH_0), and scheduled machine hours (SMH). The utilization coefficient – i.e. the ratio between PMH_0 and SMH – recorded during the study was around 90%, for the duration of 3 to 7 shifts. For long-term machine utilization a 70% coefficient was adopted, which is still slightly higher than normal (Brinker et al. 1989), but it was assumed to better reflect the easier work conditions offered by plantation forestry (Hartsough and Cooper 1999).

Table 3 shows that machine production rates are somewhat even, ranging between 12 and 14 fresh tonnes/PMH_0 (9 to 10 tonnes/SMH). This was the result of a deliberate strategy that assigned the longest hauls to the most productive machines

Table 3. Study summary.

Machine	Modified dumper	Purpose-built forwarder	Tractor-trailer system
Average payload, tonnes	16.0	8.9	7.3
Study duration, shifts	6.6	4.6	2.8
Duration of valid observations, hours	47.3	33.6	19.3
Number of valid observations (trips)	42	47	33
Mass extracted, fresh tonnes	674.2	418.8	242.6
m^3 extracted, stacked volume	956.2	593.9	341.5
Time elements in sec, mean (std. error)			
Travel empty	777.8 (24.2)	440.0 (32.8)	153.3 (11.9)
Manoeuvre	57.2 (12.0)	12.8 (5.3)	56.9 (8.9)
Load	1219.0 (30.5)	878.8 (27.0)	872.7 (26.3)
Move	134.3 (18.7)	53.1 (9.6)	41.0 (9.4)
Travel loaded	1078.8 (33.1)	579.6 (36.0)	220.9 (17.7)
Unload	747.7 (12.5)	597.9 (23.3)	560.5 (24.0)
Other	43.4 (11.5)	9.8 (5.7)	24.2 (9.9)
Delays %	11.7	9.0	15.3
Extraction distance – average, m	1640	693	174
Extraction distance – range, m	579–1973	173–1960	40–254
Fresh tonnes/PMH_0	14.2	12.5	13.6
Fresh tonnes/SMH	9.9	8.7	9.5
m^3 stacked volume/PMH_0	20.2	17.6	19.2
m^3 stacked volume/SMH	14.1	12.3	13.4

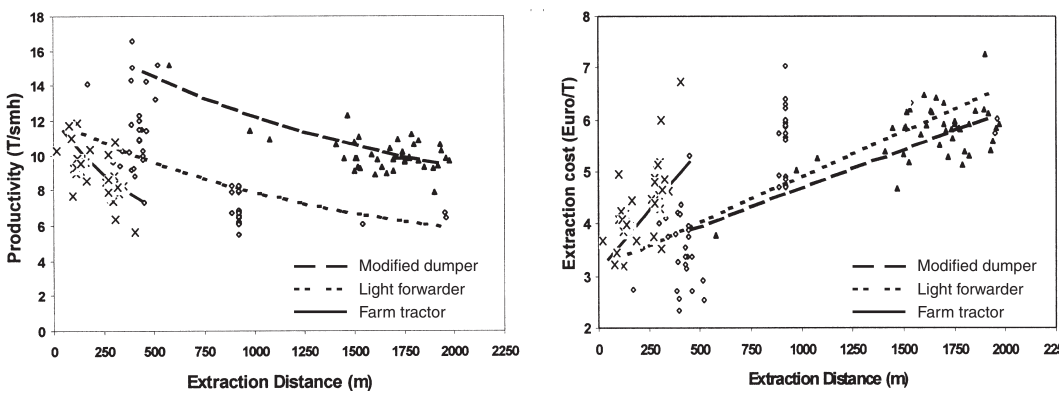

Fig. 2. Variation of forwarder productivity and extraction cost with extraction distance.

to maintain a constant supply of material to the landings: average extraction distance was approx. 170 m for the farm tractor, 700 m for the light forwarder and 1600 m for the dumper.

Comparing the potential of the three machines requires modelling their productivity, which was done through statistical analysis of their respective data sets. Effects of the key factors associated with productivity in forwarding operations (viz. travel distance, route gradient, payload and log size) were tested in a multiple linear regression of the extraction time elements (Table 4). Travel time is closely correlated to the distance covered, and also to the payload, in the case of the loaded part of the trip. As would be expected, both loading time and unloading time are a function of load

Table 4. Significant time expenditure models for the forwarders studied ($p<0.01$).

Time elements by forwarder type	Regression models, sec.	R^2	SE
Modified dumper			
Travelling empty	159.47 + 0.376 Dist	0.413	121.935
Manoeuvring	57.190	-	11.969
Loading	–952.367 + 135.259 T	0.202	178.710
Moving	134.309	-	18.700
Travelling loaded	0.655 Dist	0.979	158.123
Unloading	1.418 T / piece size	0.973	122.796
Other work	43.405	-	11.502
Purpose-built forwarder			
Travelling empty	140.783 + 0.452 Dist	0.850	88.240
Manoeuvring	12.851	-	5.324
Loading	97.730 T	0.949	202.566
Moving	53.085	-	9.581
Travelling loaded	192.120 + 0.559 Dist	0.785	115.710
Unloading	1452.112 – 6.230 T / piece size + 0.0106 (T / piece size)^2	0.281	138.534
Other work	9.808	-	
Tractor-trailer system			
Travelling empty	0.907 Dist	0.941	40.589
Manoeuvring	56.939	-	8.912
Loading	114.643 T	0.948	201.439
Moving	40.970	-	9.402
Travelling loaded	–16.712 + 1.365 Dist	0.742	52.540
Unloading	75.833 T	0.978	84.591
Other work	24.242	-	9.937

Dist = travel distance, metres
T = payload, fresh tonnes
Piece size = average piece weight, fresh tonnes

size. In the case of both the dumper and the light forwarder, unloading time is also influenced by log weight.

Trends of the evaluated machine productivity are shown in Fig. 2. The graphs were calculated for the average payloads recorded and a mean log mass of 35 kg, fresh weight. The modified dumper outperforms all the other machines i.e., it was able to extract twice their payload and was faster in almost every phase of the working cycle. The farm tractor had the lowest productivity.

Operating costs were calculated using the procedures described by Miyata (Miyata 1980), on an estimated annual utilization of 2000 hours and a depreciation period of 5 years. A machine utilization rate of 70% was assumed, while labour cost was set at 12 Euro/h. Interest rate was estimated at 8% and the insurance and tax rate at 7%. Fuel cost was assumed to be 0.75 Euro/l. The total costs are exclusive of profit and overheads. The results are operating costs of 57.4, 38.6 and 37.9 Euro/h, respectively for the dumper, the forwarder and the tractor-trailer system.

The established unit cost data (Euro/fresh tonne) and the evaluated productivity models were used to calculate the extraction cost depicted in Fig. 2. It is shown that under the conditions of this study, it was economical to use the modified dumper for extraction distances in excess of 500 m. However, the economic gain obtained in using a modified dumper becomes significant (approximately. 4%) when forwarding over more than 1 km. Below this distance, it is difficult to assess which machine is the more economic. The farm tractor was more expensive for the range of extraction distances tested (150–500 m), which suggests that it should be used only as a support unit and for shorter (<150 m) extraction distances.

3.2 Evaluation of Site Disturbance

Results of the rut depths that were recorded on the respective extraction routes are presented in Table 5.

The rutting data show a difference (significant to t-test), which represents the site impact levels typical of each forwarder. The modified dumper was by far the heaviest machine and it generated the deepest ruts (max. depth 1200 mm). With a full load, it weighted twice as much as the purpose-built forwarder, i.e. 33 tonnes vs. 18 tonnes. The tractor-trailer system was as heavy as the purpose-built forwarder, but it was much more gentle on the soil. This may depend on its inferior mobility, which prevents it from treading wet or steep spots. Of course, soil impact depends on machine ground pressure, which is related to the footprint area. This parameter was not considered in the study, because it is difficult to measure it correctly in its dynamic dimension. However, for similar machine configurations as those used for the study (i.e. 6-wheels, standard tyres, max. inflation pressure) machine weight may represent the main impact factor and rut depth may prove a good indicator of respective impact levels.

The average extraction trail spacing of 35 m results in a trail density of 285 m/ha. For a 3.5 m trail width, the total ground surface covered by extraction trails is 10% of the forest land. In plantation forestry, the levels of rutting due to the extraction machines and the associated compaction are of concern. An effective strategy may consist in the provision of a permanent extraction trail network, to minimize site impacts with each rotation. Furthermore, one may reduce the severity of rutting by limiting the recourse to modified dumpers. These machines are generally resorted to because of the long extraction distances: therefore, the solution may consist in reducing the extraction distance by increasing the density of the forest roads. If we set an economically acceptable break-even point of choice between a modified dumper and a light forwarder to approx. 1000 m, the corresponding road density may be evaluated from (FAO 1974):

$$\text{Dist} = \frac{k}{\text{RD}}$$

Table 5. Summary of the rut measurements.

Machine	Modified dumper	Purpose-built forwarder	Tractor-trailer system
Trail length sampled (m)	3496	1730	273
Trail width (mm)	3500	3500	3500
Avg. rut depth (mm)	500	200	80
Max. rut depth (mm)	1200	550	200
Avg. trail gradient (%)	8	11	9
Max. trail gradient (%)	23	36	20

where
Dist = average extraction distance (km)
RD = road density (m/ha)
k = terrain factor = 4 to 5 in flat terrain
5 to 7 in hilly terrain
7 to 9 mountain
>9 very steep mountain

Considering a terrain factor (k) of 6 as for hilly terrain, the road density that would allow the purpose-built forwarder to remain competitive with respect to the modified dumper is 6 m/ha. Whenever possible, the forest road network should be upgraded accordingly. It is suggested that further cost-benefit analyses are conducted on this subject, in order to calculate the cost of an eventual upgrade, as well as its multiple benefits, including: reduced erosion, reduced deactivation costs, easier surveillance and safer fire prevention/control. Of course, the break-even extraction distance will change with changing machine cost assumptions: this report gives just one possible distance, but it also provides readers a model for recalculating the break-even distance under their own cost assumptions.

The tractor-trailer system was excluded from the comparison because it is not an economical alternative to either the dumper or the light forwarder: it is rather a complement to the main forwarding fleet, whichever machine this is based on.

4 Conclusions

Overall, extraction productivity may vary from 6 to 15 fresh tonnes/SMH, which is not much different from what is documented by other studies of standard Scandinavian forwarders, if the long extraction distance is taken into account. Under the economical assumptions of the present study, extraction cost ranges from 3.5 to 6.5 Euro/fresh tonne. The modified dumper is the most-productive unit, and given its higher speed and larger payload, it is the economic choice for extraction distances in excess of 1000 m. However, it also generates the most severe rutting, hence it should be used with caution. For extraction distances below 1000 m, the light purpose-built forwarder compares favourably with the modified dumper, while generating less than half the site disturbance. The tractor-trailer combination is economically inferior to the modified dumper and the light forwarder, and should be regarded as a complement to the main extraction fleet and where short-haul operations are required.

From the operational viewpoint, one should explore the possibility of increasing the road density in order to reduce extraction distance. This would allow the economical use of the light forwarder, which generates less rutting and probably less soil disturbance in general. Further studies should focus on the overall economic balance of such strategy, and evaluate the economical impact of road building on extraction cost. Once a model is available, different scenarios can be simulated in order to select the best overall strategy for each set of conditions.

Acknowledgements

This study was funded by the European Commission under the 5th Framework Program on Quality of Life and Management of Living Resources, Contract No. 1999-00991 (Ecowood). The authors wish to thank Piergiorgio Fabbri (CNR/TTI, Sesto Fiorentino, Italy), Carla Nati (CNR/TTI, Sesto Fiorentino, Italy), Julio Molano-Sanchez (Sefosa SA, Sevilla, Spain) and Martin Ziesak (LMU, Munich, Germany).

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Appendix I. Notations used.

CTL	=	cut-to-length
PMH_0	=	productive machine hours excluding all delays (hours of productive work time as described by Björheden et al. 1995)
SD	=	standard deviation
SE	=	standard error
sec	=	seconds
SMH	=	scheduled machine hours (hours of workplace time as described by Björheden et al. 1995)
1 m^3 stacked volume	=	a wood stack occupying the space of 1 m^3