Productivity Norms for Harvesters and Processors USED in Italy

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Abstract:
Harvesters and processor working in Southern Europe face specific work conditions, which may significantly affect their productivity. Starting from this consideration, the authors developed a general productivity model for the harvesters and processors currently used in Italy. The model consists of a set of mathematical relationships that can estimate the productivity of these machines under the whole range of specific work conditions faced in Italy. Such relationships can provide general directions to prospective users, and can contribute to the development of scenario predictions. The original data pool contained over 15,000 individual time-study records, each representing a single harvesting cycle (most often one tree). The records were extracted from 38 studies conducted with the same methods and by the same principal investigators between 1998 and 2008. Statistically significant models were developed for all cyclic work phases, such as moving, brushing, felling and processing. Accessory time and delay time were added as percent factors, also estimated from the same studies. Model development aimed at achieving the best compromise solution between accuracy and easy use, avoiding the introduction of an excessively large number of input variables. Selected independent variables were: tree volume, tree species, task type (harvesting or processing), machine power and type, density of residual stand and of harvest trees, stand type, and slope gradient. These models could predict a large proportion of the variability in the data and were successfully validated using reserved cycle records, extracted from the same data pool and not used for model development. Comparison with similar Nordic and German standards confirmed the sound structure of the Italian models, while highlighting the need for specific productivity norms.

Keywords: harvester, processor, productivity, standards, model

1 Introduction

Originating from a purely Scandinavian background, the mechanized cut-to-length (CTL) system has gained world-wide acceptance, expanding far beyond the limits of boreal forestry. Harvesters and processors have also become very popular in Mediterranean countries, such as Spain, Portugal, and Italy, where they perform much of the harvesting in the industrial pine, eucalypt and poplar plantations. Their cost-effective deployment requires a reliable estimate of the productivity achieved under a range of conditions. Most of the studies currently available for the use of mechanized CTL technology under non-Nordic conditions have an episodic character, and are not the best material for making overall predictions. These should be based on overall productivity models, built on very large samples where variation caused by the human factor can be levelled out by including several professional operators in the same general study (Nurminen et al. 2006). To date, very few such studies are available to the international scholar, and they all concern Nordic operations. Productivity standards have been developed in Sweden (Brunberg 1995 and 1997), and a similar reference is now available for thinning in Finland (Sirén and Aaltio 2003). No overall productivity reference is yet available for Central and Southern Europe, where the extrapolation of Nordic results might lead to significant errors since working conditions, operator training, and technological solutions are quite different and are likely to affect machine performance. The goal of this study was to develop a general productivity model for the harvesters and processors currently used in Italy, where mechanized CTL harvesting was introduced over 10 years ago, and is now spreading to a large variety of operations (Spinelli et al. 2010). Here, the conditions encountered by CTL units are very different from those found in the Nordic countries and include: mountain forests, hardwoods, close-to-nature forestry, and industrial poplar plantations. This study aims at calculating a set of mathematical relationships that can estimate the productivity of CTL units under the whole range of specific work conditions faced in Italy. Such relationships can provide general directions to prospective users, and can contribute to the development of scenario predictions. Furthermore, the comparison between these eventual standards and those developed for Northern Europe can help gauge the differences between the Nordic and the Southern European working environment, thus addressing the main issues for future technical developments. Finally, the information obtained from the models can easily be extended to countries in which work conditions are similar to those in Italy, at least until specific local models become available.

2 Materials and Methods

The authors compiled the raw data from 38 complete time studies, conducted between 1998 and 2008 by the researchers of the Italian National Council for Research (CNR). All the time studies were set up and carried out by the same principal investigator and with the same methods. Productive time was separated from delay time (Björheden et al. 1995), and split into functional elements, expected to react to different variables (Bergstrand 1991). Delay-free time per tree was subdivided into five basic elements: *move* (at roadside or within the stand), *brush* (occurring only if operating within the stand), *grab* (if processing at the deck) or *fell* (if harvesting within the stand), and *process* (delimbing and bucking). *Move* activity within the stand is inherently different from that at the road, so the two cases were recorded and analyzed separately. Grabbing a stem from a pile is also different than felling a standing tree, justifying separate evaluation. On the other hand, processing was considered to be similar in character whether conducted in the stand or at the landing, so the data were combined for analysis and an indicator variable was used to check for differences between the two cases, as suggested for harvesting work studies (Olsen et al. 1998). The merchantable over bark volume processed during each cycle was also recorded, and associated to the observation data. All time-motion data were recorded with Husky Hunter® hand-held field computers running Siwork3® time-study software.

Almost 60 percent of the studies concern general-purpose prime movers, such as tracked or wheeled excavators, flexible-legs excavators (so-called “spiders”), and farm tractors. In Italy, most loggers are relatively new to mechanized CTL harvesting and are afraid of the strong commitment required by the purchase of a dedicated harvester. Besides, the superior agility of such units might be unnecessary if they are to be deployed in flatland row plantations, or by the roadside, under a yarder.

The data base represents 19 different professional operators, generally experienced and proficient. All operators worked single shifts with occasional overtime, so that fatigue was unlikely to significantly affect performance. The overall data set contains 15,148 cycle observations corresponding to 15,366 trees. Multi-tree handling (i.e., handling more than one tree per cycle) was observed on rare occasions, exclusively when processing felled trees from a deck. Tree volume ranged from 0.010 to 7 m^3, with an average value of 0.346 m^3. Total study volume amounts to 5239 m^3 and study time to 329 hours of net work, excluding all delays. Average productivity is 46 trees or 15.9 m^3 per net hour, excluding all delays.

We used regression analysis of the time-study data to develop a set of equations capable of predicting cycle time (and therefore productivity) as a function of statistically significant independent variables. Validation was conducted according to the same procedure recently used by Adebayo et al. (2007) for a similar modelling study. The dataset was partitioned at random into two subsets: the first subset, containing 70 percent of the observation number was used to calculate appropriate productivity relationships through regression analysis; the second subset, with the remaining 30 percent of the observations (reserved data), was used to validate the regressions obtained above. To this purpose, the time consumption equations were used to predict the reserved data, then the predicted cycle times were correlated with the observed cycle times, and the resulting r^2 (validated r^2) was used as a measure for the predictive capacity of the equations. Furthermore, two-sample t-tests were used to test the differences between predicted and observed cycle times.

3 Results

Regression analysis of 70 percent of the original data pool allowed estimating six equations, capable of predicting the time consumption for each individual work phase, namely: *move* time at deck, *move* time in the stand, brushing time, felling time, time for grabbing a tree from a deck, and processing time.

Move time at deck when processing pre-felled trees was not significantly related to tree volume, and was highly variable. This can be expected because when processing trees from a deck, the machine can reach many stems from the same position. *Move* time also depends on a number of factors that could not be included in the model, such as decking layout and operator ability to organize the work in the most effective way. The predictive equation is reported below (n= 5693, r^2 pred. = 0.008):

Move at deck, 10^{-2} min tree^{-1} = 5.6 + 4.26 tree volume, m^3 **(1)**

Move time within the stand increased with slope and the number of residual trees per hectare, and decreased with the number of removed trees per hectare and with the power of the prime mover. Time per tree was substantially longer for spider- or tractor-based harvesters, which are somewhat awkward compared to dedicated harvesters and excavator base units. The predictive equation shows a weak correlation (n= 5643, r^2 pred. = 0.091):

Move within stand, 10^{-2} min tree^{-1} = 7.5 + (12412 + 771 Slope gradient (%)

+ 46706 Spider dummy + 63153 Farm tractor dummy)/ (Removals, tree ha^{-1}

* (Machine power, kW)$^{0.5}$) + 0.204 * Residuals, tree ha^{-1} / (Machine power, kW)$^{0.5}$ **(2)**

Brush time is the time needed to clean the undergrowth from around removal trees, and only applies to harvest (versus processing), which involves access to the stand. No *brush* time is needed when processing trees from a deck. *Brush* time per tree was greater under forest conditions than in plantations, the latter generally presenting much sparser undergrowth. This element also had inherently high variability (n= 5,641, r^2 pred.= 0.020):

Brush, 10^{-2} min tree^{-1} = 1.8 + 9.2 Forest dummy **(3)**

Grab time from a deck increased with tree size and decreased with machine power. Spider-based machines took roughly twice as long as others of the same power to grab a tree. The coefficient of determination is much higher than in the previous equations, due to a much more stable work routine (n= 5,693, r^2 pred.= 0.162):

Grab, 10^{-2} min tree^{-1} = 15.2 + 153.1 tree volume, m^3 / (Machine power, kW)$^{0.5}$

+ Spider dummy * (13.9 +274.9 tree volume, m^3 / (Machine power, kW)$^{0.5}$) **(4)**

Fell time within the stand increased almost linearly across the observed ranges of tree volume, for most machines. Time decreased with machine power and increased with gradient for all but the spider-based harvesters, which seem insensitive to slope gradient during the felling operation, within the limits explored by the study. Time consumption was greater for the excavator-, tractor- and spider-based machines, compared to the dedicated harvesters. The equation below is highly significant (n= 5,122, r2 pred. = 0.472):

Fell, 10^{-2} min tree^{-1} = 3.8 + 156.5 tree volume, m^{3} / (Machine power, kW)$^{0.5}$ + 1.18 Non-spider

dummy * Slope gradient, % + 6.5 Excavator dummy + 24.8 Farm tractor dummy +

Spider dummy (25.5 + 188.5 * tree volume, m^{3} / (Machine power, kW)$^{0.5}$) **(5)**

Process (delimbing and bucking) time per tree increased with tree volume, number of logs and gradient, while it decreased with machine power. Stroke processors (versus roller or track-type heads) and tractor-based machines required more time than other types. There was no significant difference between the processing times recorded for roadside work and for work within the stand, other factors being equal. Processing of chestnut and poplar required less time than for conifers, other factors being equal. This is logical, because poplar clones are selected for straight stems and are usually pruned, whereas chestnut is always in the form of coppice sprouts, generally slender and with few branches. Other hardwoods – generally branchy and badly formed – took more time to process than did the conifers. The regression shown below is highly significant (n= 11,324, r2 pred. = 0.670):

Process, 10^{-2} min tree^{-1} = 22.7 + 1.433 tree volume, m^{3} * Slope gradient (%)

+ (1155 + 446 Stroker dummy + 2244 Farm tractor dummy - 362 Chestnut or Poplar dummy + 1118 Other Hardwood dummy) * tree volume, m^{3} / (Machine power, kW)$^{0.5}$ **(6)**

The validity of all the equations above was checked by comparing the predictions and the actual values for the second subset, specifically reserved for the purpose. Table 1 reports the actual and predicted values, the percent error for the estimates, the results of the paired t-test conducted between the two groups of data (actual and predicted) and the coefficients of variations for the respective regressions (actual vs. predicted). Where the paired t-test indicated that the difference between the two groups was not significant, the prediction was accepted as valid. The limit for significance was assumed to be the usual $p < 0.05$. The coefficient of variation was taken instead as a measure for the reliability of individual predictions conducted at cycle level. The trend was considered valid whenever the coefficient of variation for the actual vs. predicted was of the same magnitude as the coefficient of variation recorded for the predictive equations. Four equations out of six appear to be validated, whereas correction factors should be applied to the predictions obtained from equations 2 (*Move* in stand) and 5 (*Fell*). In any case, the error is limited and represents respectively -2 and -3.5 percent.

The equations presented above allow estimating cyclic net time, which can be transformed into scheduled time consumption by adding appropriate estimates for accessory time and delay time.

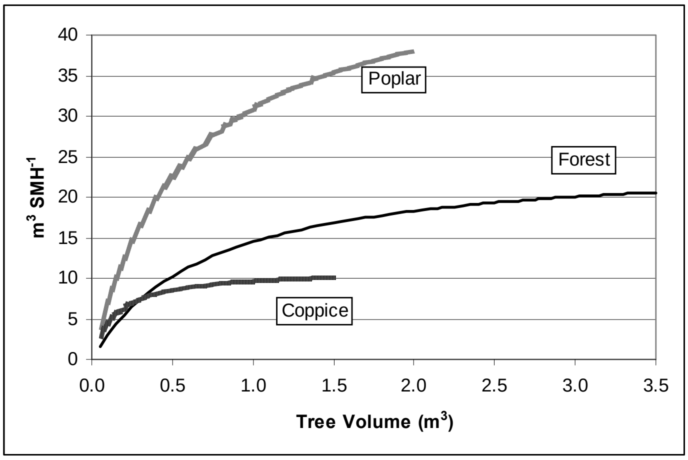
Table 1 - Results of the validation tests

Eq. no.[1]	Element	Actual	Predicted	Δ %[2]	t-test p	r^2 val.[3]	r^2 pred.[3]
1	*Move* at deck	7.5	7.1	-5.3	0.559	0.009	0.008
2	*Move* in stand	19.6	14.4	**-26.5**	<0.0001	0.098	0.091
3	*Brush*	1.2	1.1	-8.3	0.458	0.051	0.020
4	*Grab*	22.0	21.2	-3.6	0.158	0.121	0.162
5	*Fell*	29.2	26.8	**-8.2**	<0.0001	0.401	0.472
6	*Process*	67.6	68.2	0.9	0.701	0.685	0.670
-	Total at Deck	99.7	97.8	-1.9	0.068	0.684	-
-	Total in Stand	114.5	110.5	**-3.5**	0.002	0.558	-

In the cases observed, accessory time mostly consisted of tasks such as slash piling, log stacking and log sorting, These tasks are not cyclic and occur every so often, after harvesting or processing a certain number of trees. Therefore, inaccurate results can derive from attaching the time consumption for a specific occurrence to one specific observation. As an alternative, we developed percent coefficients that relate the duration of accessory time to the duration of cumulative cyclic time, in order to reflect the indirect effect of tree size and shape on accessory time, on the assumption that bigger trees are likely to produce more slash. Two percent coefficients were developed, equal to 14.7 percent (Std. Deviation 34.3) and 29.6 percent (Std. Deviation 81.8) respectively for harvesting in the stand and processing at the deck. The development of different coefficients for the two different work types was justified by a t-test, demonstrating that the two work types actually presented a significantly different incidence of accessory time ($t = 14.5$, $p < 0.0001$, DF = 15138).

Delay time can be added to productive time using appropriate coefficients, in order to reflect actual scheduled time, which is the time to be paid for. This practice is common in Nordic studies (Kuitto et al. 1994) and specific coefficients have recently been developed for harvesters and processors operating in Italy (Spinelli and Visser 2008). Such coefficients represent a percent incidence and are applied to the sum of productive and accessory time to calculate the duration of delay time. Different coefficients were developed for harvesting work in natural forests, harvesting work in plantation forests and processing work from decks.

Figure 1.–Predicted overall productivity in m^3 SMH^{-1}.



An example of the use of our models is shown in figure 1, representing an estimate of overall productivity for three of the most common cases in Italy, namely: the harvesting of spruce with a dedicated harvester (160 kW), the harvesting of plantation poplar with an excavator-mounted harvester (130 kW) and the processing of hardwood stems at the roadside, with an excavator-based processor (75 kW). The delay coefficients were 50, 21, and 44 %, respectively, and the assumed slope gradients were 2, 25, and 2 %. The dedicated harvester was assumed to be working in a spruce selection cut, with a prescribed removal of 150 trees ha^{-1}, representing 50percent of the original tree density. Tree volume was adjusted for the respective ranges, and productivity is reported in m^3 per Scheduled Machine Hour (SMH).

4 Discussion and Conclusions

This study is unique because of the wide range of equipment observed and the very substantial size of the dataset, suitable for representing a large variety of machines and operations. A further asset of the study is that all data were collected by the same principal investigators, which limited errors caused by different interpretations of the same data collection protocol. In fact, the collection of such a large data pool required approximately 10 years, and was a rare endeavor.

As in numerous previous studies, tree volume was found to be a primary variable affecting the total time to harvest or process a tree. Following careful analysis of source data, this study elected a linear model to represent the relationship between time consumption and tree volume, as already done by other authors (Hanell et al. 2000, Sirén and Aaltio 2003, Nakagawa et al. 2007). It is therefore important to avoid extrapolation beyond the range of tree volumes contained in the origin data, which is however quite wide, and ranges from 0.005 to 7 m^3.

The models also include several other independent variables, such as slope gradient, stand type and tree density, all of which are known to affect time, especially moving. On the other hand, the models did not integrate tree selection criteria, which impact productivity both in thinning (Eliasson 1999) and in final cuts (Hånell et al. 2000). However, the same authors also indicate that the effect of different selection criteria is often mediated through variations in tree size, so that our models can indirectly reflect tree selection criteria (Eliasson and Lageson 1999).

The study also allowed us to quantify some important effects of machine type and size, the latter indicated by the rated power of the prime mover. More power resulted in less time consumption for the same task, which applied to most work phases. Head size did not have any significant effect on productivity when considered in addition to machine power, but head type did. Stroke-type heads proved significantly less productive than roller- or track-type heads, as expected. The analysis also showed that dedicated carriers had higher productivity than others, and in particular that tractors and spider bases were particularly slow in most tasks, possibly because of less effective design for the observed tasks. On the other hand, spider-base units were the only ones to be found indifferent to slope gradient when felling, which makes them an interesting option for steep terrain harvesting. In fact, the models developed with the study can help determine a break-even slope gradient, above which a spider-base harvester will offer better results than a dedicated unit, thanks to its superior steep terrain mobility. In this respect, Figure 2 shows the results of a simulation conducted for a hypothetical spruce stand with removals of 150 trees ha^{-1}, (50% of the original stocking), and an average tree size of 0.3 m^3. The simulation included the same 160 kW dedicated unit described earlier on and an 88 kW spider-based harvester. Slope gradient was varied from 0 to 50percent-- the simulation indicating that beyond a 40percent slope gradient the spider is more productive than the dedicated harvester.

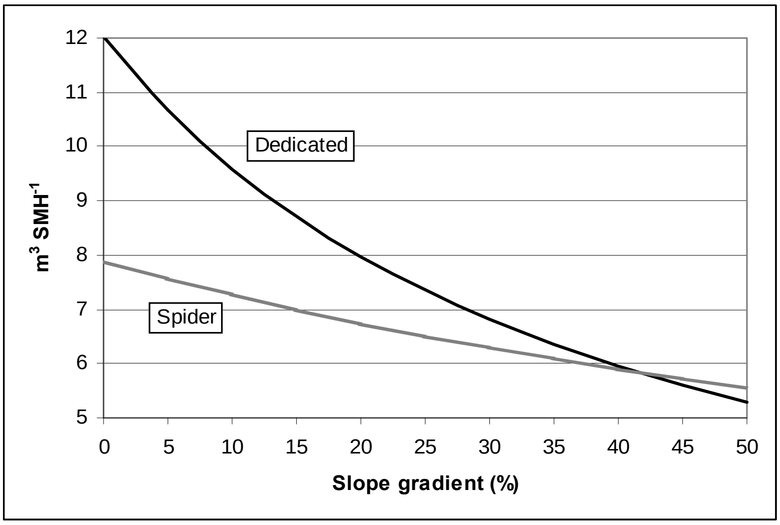


Figure 2.–Dedicated vs. spider-based harvester in young spruce selection cut (avg. vol tree = 0.3 m^3).

In contrast to some other studies, we did not find any explicit productivity effects of clearfell versus thinning, although these discrete differences may have been partly covered by the significant effects of removal and residual trees per hectare on *move* time, and by the pervasive effect of tree size, which is strongly correlated to silvicultural treatment. In fact, clearfell is being progressively banned from Italian forests, by limiting the area of clear-cuts. Group or single-tree selection represents the main type of maturity cut applied to Italian forests, with the exception of coppice stands and short-rotation plantations. Coppice trees are generally felled by chainsaw, because of the inherent difficulty of cutting multiple trees sprouting from the same stump, so that processors rather than harvesters are used in coppice harvesting operations. Therefore, the only real clearfell work performed by Italian harvesters is in poplar and pine plantations.

The models in this study are relatively accurate, and can explain a large proportion of the variability in the process. The remaining error most likely depends on a number of other variables that were not included in the study. Some of these were difficult to introduce, because their translation into suitable indicators would have required a subjective judgment by the researcher. Other variables were easier to record, and some of them were indeed recorded for at least part of the 38 origin studies. However, it was estimated that the inclusion of these further factors into the model would have complicated its use more than it would have increased its value. The risk was that users could be overwhelmed by the number of input data necessary for the model to return its estimate, and would provide approximate figures, thus canceling the benefit of increased model accuracy. Requiring only a few and relatively simple input data, this model was designed to offer a best compromise solution and prove both user-friendly and reasonably accurate.

Finally, it may be interesting to see how the Italian productivity standards, tentatively developed with this study, compare to the standards reported by other authors for other countries. To this purpose, three general models were selected, all designed to represent a cross-section of mechanized operations in a given country, and generally based on large datasets. Two models were those developed for Sweden and Finland, respectively by Brunberg (1995) and Nurminen et al. (2006), already mentioned in the Introduction. A third and very interesting model was developed by Purfürst (2007) in Germany, using an extremely large data pool made of the records extracted from the on-board computers of about 30 machines. All three models calculate productivity after excluding delays longer than 15 minutes, and their results are not directly comparable with those obtained from the Italian model, which estimates productivity after including all delay time. Therefore, the delay factors on the Italian model were changed for the purpose, by applying a reduction factor of 0.39, also calculated from Spinelli and Visser (2008). The Italian comparison treatments were clearfell harvesting of spruce and poplar, performed with a dedicated harvester, in order to reflect conditions similar to those in the foreign studies. The results are reported in Figure 3. The estimated productivity for the harvesting of Italian spruce is the lowest, and it is somewhat nearer to the estimate for Germany than to those for Finland and Sweden. That may partly depend on the heavier branching of Alpine spruce, so that the descending southern gradient of spruce harvesting productivity might be related to a comparable and increasing branching gradient. In a way, Nordic softwood stands may offer conditions that are more similar to Italian poplar plantations than to alpine spruce forest, which might be the reason for the very similar productivities achieved in both stand types. In fact, the estimated productivity for Italian poplar is extremely close to that obtained for Swedish spruce, with the two graph lines almost overlapping. The results of this comparison are a good witness to the sound structure of the Italian models, which return reasonable and justifiable figures. At the same

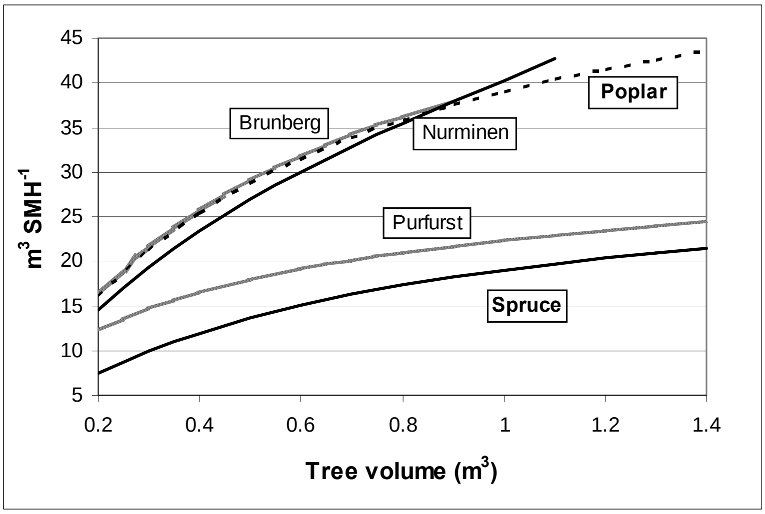


Figure 3.–Comparing the estimates for Italian spruce and Italian poplar with those obtained from some other popular models for softwood harvesting.

time, they highlight the specific conditions of Italian forest operations, and support the need for specific models.

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