SILVA FENNICA

Silva Fennica 42(5) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

The Effects of Increased Mechanization on Time Consumption in Small-Scale Firewood Processing

Ola Lindroos

Lindroos, O. 2008. The effects of increased mechanization on time consumption in small-scale firewood processing. Silva Fennica 42(5): 791–805.

Firewood, which is mainly processed by the consumer, is still an important source of energy for heating houses in industrialised countries. Possibilities to compare the mechanization's impact on efficiency of firewood processing are limited, due to variations between working conditions in previous studies. Therefore, the objective was to compare time consumption for two small-scale firewood processing systems with different levels of mechanisation under identical conditions. The systems were tested on two classes of wood: one with a homogeneous and medium-sized diameter of logs and one with a mixture of small and large-diameter-logs. Differences in time consumption were analysed for correlations with physical workloads, deviations to routine operations, operator influences and operator perceptions. Twelve operators (60–79 years old) were studied and they showed large variation in time consumption. However, the within-operator time consumption patterns were consistent. In other words, operators all responded similarly to the different combinations of systems and wood classes, but at different absolute levels. The time required to process a unit volume of wood was 25–33% lower when the more highly mechanised system was used, and the time required was 13–22% lower for the homogeneous wood class. Physical work load, deviations and perceptions of the work varied between operators, but were weakly correlated with time consumption. The results' implications for analyses of investments in equipment for firewood-processing for self-sufficiency purposes are discussed.

Keywords comparative time study, fuelwood, blade saw, wedge splitter, processor, senior worker, operator effects
Addresses Swedish University of Agricultural Sciences, Dept of Forest Resource Management, SE-901 83 Umeå, Sweden
E-mail ola.lindroos(at)srh.slu.se
Received 19 February 2008 **Revised** 26 June 2008 **Accepted** 28 August 2008
Available at http://www.metla.fi/silvafennica/full/sf42/sf425791.pdf

1 Introduction

Situations where working practices are still labour-intensive in industrialised countries are often those where labour costs and/or investment capacities are low. This notably applies to sectors dominated by people motivated by a desire to be self-sufficient for given products including, to a certain extent, forestry in the Nordic countries. Industrial forestry was subject to rapid mechanisation in the last half of the 20th century, leading to equipment such as modern harvesters and forwarders, while mechanisation of the self-employed family forestry sector proceeded more slowly (Lindroos et al. 2005). Nevertheless, small-scale forest equipment has developed simultaneously with its large-scale equivalents through adapting and implementing new technical solutions for small-scale applications. However, high productivity is also often associated with high purchase costs, so the volume of income-generating products per annum needs to be sufficient to warrant its use rather than the use of less productive but less expensive equipment (Gullberg 1991). In cases of self-sufficiency uses, however, the constraints imposed by fixed and often low production volumes restrain investment frames in order to minimize costs (Gullberg 1991).

The mechanization of firewood production can be seen as a parallel, in terms of productivity and investment relations. Firewood production is principally conducted for domestic heating needs, which for a household in the Nordic countries normally amounts to less than 35 m^3 of solid wood per year (Sundin 1982, Isachsen 1984, Moe 2007). Nevertheless, firewood is highly important, since it supplies 21.6% of the energy required for heating detached houses in Sweden (Statistics Sweden 2003) and accounts for 1.5% of the country's total energy consumption (National Board of Forestry 2005). The firewood production is self-paced, mainly conducted on a leisure time basis, and thus is more project-based than work hour-based. The work generates little or no revenue in terms of actual income, but reduces costs by avoiding purchases of firewood or alternative energy sources. Firewood production is characterised by highly repetitive operations using simple, but potentially dangerous, equipment. Severe accidents commonly occur (Wilhelmson et al. 2005) and accident rates per work hour are higher than in most other activities (Lindroos et al. 2008). However, little is known about the persons conducting the work, although they have been assumed to be closely related to those engaged in self-employed forestry. Self-employed forest owners in Sweden are predominantly men, a majority is more than 50 years old (Lindroos et al. 2005) and these features also apply to firewood-producing persons, according to a recent survey (Moe 2007). For most kind of professions and work types, persons older than 60 years only constitute a small proportion of the workers. In firewood processing, on the other hand, 31% of the active persons are older than 60 years and they contribute with 43% of the worked hours. In fact, several studies have found that people continue to process firewood beyond the age of 80 years (Lindroos et al. 2008, Wilhelmson et al. 2005, Moe 2007) and the activity's high value in terms of recreation and work satisfaction for people of such high ages has also been noted (Carlsson 2003). Nevertheless, studies of elder workers' efficiency in firewood processing are rare (Table 1).

Annual sales of firewood machines are substantial in Sweden. In 2002 the number of sold new machines amounted to 13 211, distributed on 152 models (Lindroos et al. 2005). The most common types are blade cutters, hydraulic wedge splitters and firewood processors (Lindroos 2004). The last of these performs both cutting and splitting, either sequentially in various ways, or simultaneously through cutting and splitting edges. There have been several studies on the productivity of firewood-processing systems with different levels of mechanisation (Table 1). For the partly mechanised system of blade cutter and screw or wedge splitter, 22–86 min is required to process 1 m^3 solid wood on bark. A processor with a blade cutter and a wedge splitter is a more mechanised system and requires between 24–46 min m^{-3}, while a large, industrial-oriented processor requires just 7 min m^{-3}. However, between-system comparisons and assessments of the effects of mechanization are complicated by variations in the capacities of the machines, raw material, billet dimensions, operators and work organization. Operator numbers are often small in work studies for practical reasons,

Table 1. Reported productivity in firewood processing work studies.

Equipment	Time consumption (min m^{-3})	Billet length (cm)	Logs' mean diameter (cm)	Study extent (operators; m^3)	Operators' age (years)	Reference
Chain saw and:						
– axe	60.0	35 & 50	12	2; 2.2	25–35	(Granqvist 1993)
– wedge splitter	43.5	50	14	2; 1.6	25–35	(Granqvist 1993)
Blade cutter and:						
– axe	93.6	35	–	8; 7.8	34–59	(Liss 1996)
– screw splitter	85.7 & 64.0	33	10 & 15	2; 1.1	–	(Kärhä & Jouhiaho 2003)
	47.6 & 40.5	35 & 50	11	2; 1.3 & 1.6	25–35	(Granqvist 1993)
	42.9 & 31.6	25	10 & 15	– ; 0.3	–	(Swartström 1986)
– wedge splitter	42.9 & 22.2	25	10 & 15	– ; 0.3	–	(Swartström 1986)
Processor with blade cutter and wedge splitter:						
	46.2 & 42.9	30 & 45	10–15	– ; 15	–	(Uppgård 1996)
	37.5 & 19.4	25	10 & 15	– ; 0.3	–	(Swartström 1986)
	30.0 & 18.8	50	10 & 15	1; 0.9	–	(Björheden 1989)
	26.2 & 13.7	33	10 & 15	2; 42.5	–	(Kärhä & Jouhiaho 2003)
	24.2 & 25.6	35 & 50	13	2; 2.5 & 2.7	25–35	(Granqvist 1993)
	7.1 & 6.7	40	18 & 21	1; 8.3 & 8.7	–	(Folkema 1983)
Processor with simultaneously cutting and splitting edge:						
	54.5 & 28.6	40	10 & 15	– ; 0.3	–	(Swartström 1986)
	30.0 & 14.3	30 & 50	10–15	– ; 15	–	(Uppgård 1996)
	22.8 & 18.9	36 & 48	12	2; 3.2 & 2.6	25–35	(Granqvist 1993)
	22.2 & 37.5	40	10 & 15	– ; 0.3	–	(Swartström 1986)
	7.9	45	10	2; 23.1	–	(Jouhiaho 2004)

– = missing data

even though operator effects are considerable (e.g. Hansson 1965, Björheden 2001, Ovaskainen et al. 2004) and might invalidate generalisations of the results. Strategies applied to account for these variations in the Nordic countries have involved the use of relative, within-operator productivity comparisons (Harstela 1988). Such strategies may account for within-operator variability, but yet, knowledge of some of the other variables' effects in previous studies is limited. Raw material differences, for example, have mainly been studied in terms of logs within given diameter classes, although logs of varying diameters are likely to be handled together in normal small-scale production. Furthermore, productivity studies have often focused on commercial production of firewood (e.g. Folkema 1983, Borschmann and Poynter 2003, Jouhiaho 2004), in which the productivity and economic parameters are generally very different from those that apply to small-scale family forestry. When focussing on small-scale production, studies have compared firewood with alternative sources of fuel for house heating (Isachsen 1984) rather than choices of processing system. Increased levels of mechanisation in systems often imply increased complexity, and thus possibly higher sensitivity to deviations (i.e. errors and malfunctions). Deviations in planned production procedures have been studied to some extent in firewood processing (Björheden 1989, Etting 2002), but have not been quantified and their effects on processing efficiency have not been considered.

The objective of this study was to compare time consumption for two small-scale firewood processing systems with different levels of mechanisation. Differences were analysed for correlations to raw material features, physical workloads, work deviations, operator influences and operator perceptions. The study was conducted with operators of age 60–79 years old, in order to also provide lacking productivity data for this large category of firewood processing workers.

2 Material and Methods

Two systems were studied; one including two machines and the other including just one machine. Wood of two classes was processed in tests with each machine, resulting in six treatments (3 machines × 2 wood classes). Each day was divided into three 90-minute shifts and an individual operator worked on all treatments over a two-day period. In total, 12 operators were randomly assigned to treatment orders and work days.

The first system consisted of a blade saw and a hydraulic wedge splitter, hereafter called cutter and splitter. The whole system is called system *cut-split*, with which the two steps in the processing were conducted separately in both time and space. The second system consisted of a firewood processor, hereafter called processor or as a system, system *proc*. The main machine components were identical with those in system *cut-split* (Table 2), but integrated in its design. Hence, the two processing steps were separated in time but integrated spatially. A chunk that was cut off a log fell into the machine's splitting department and the operator actuated the splitting and waited until it had been split before the next cutting. Manual loading of chunks to be split was thus avoided. All three machines were electrically powered and produced by Lennartsfors AB, Sweden (Table 2). Two machine modifications were made prior to the study. The cutter and splitter's log loading roller at the end of the log carriage was moved 30 cm beyond its original maximum extended position, to allow it to handle the long logs used in the study. To harmonize with the splitter's four-splitting axe, the processor's axe centre was adjusted to a lowest height of 10 cm. During operation, both systems were used conjunctly with a conveyor, which removed the work's end products. The two conveyors used were of the same model (108) and produced by Lennartsfors AB, Sweden. The conveyor belts' angle of inclination was 33° and the horizontal transport distance was 3.6 m.

Two operators worked simultaneously during each study day. To allow this, two equivalent working stations were used (Fig. 1). Each operator worked at the same station throughout the study. Thus, the machines were moved between stations in a pre-determined order during each work day. The distance between the two working station was 14 m and a tarpaulin prevented visual contact. Between each working day's three shifts, 95 min (standard deviation (SD) 17, interval 64–131) of rest with sustenance was taken. Operators had at least one day's rest between workdays.

The study was conducted between 11 November and 2 December 2005 in Vindeln, Northern Sweden (64°12 N, 19°43 E), in an illuminated (>125 lux at work height) building with asphalted ground and roofing, but no walls. The air temperature during the study was –3°C (SD 4°C). At each work station, the same log loading table was used for both the cutter and processor. Two

Table 2. Data on firewood processing machines in the study.

Feature	System cut-split		System proc
	Cutter	Splitter	Processor
Model [a]	114	60E	2000E
Maximum power (kW)	4	4	4
Hydraulic pushing force (kN)	n.a.	69	69
Hydraulic piston's stroke time (s)			
– full length extension and retraction	n.a.	4	4
Circular blade diameter (mm)	700	n.a.	700
Maximum cutting diameter (cm)			
– with/without re-cut	35/23	n.a.	35/23
Maximum splitting length (cm)	n.a.	60	60
Work height (cm)	87.5	76.0	87.5
Mass (kg)	140	131	272
Purchase price (€) [b]	905	932	2843

[a] All models were made by Lennartsfors AB, Sweden. [b] Year 2005, value added tax and freight excluded; n.a. = not applicable.

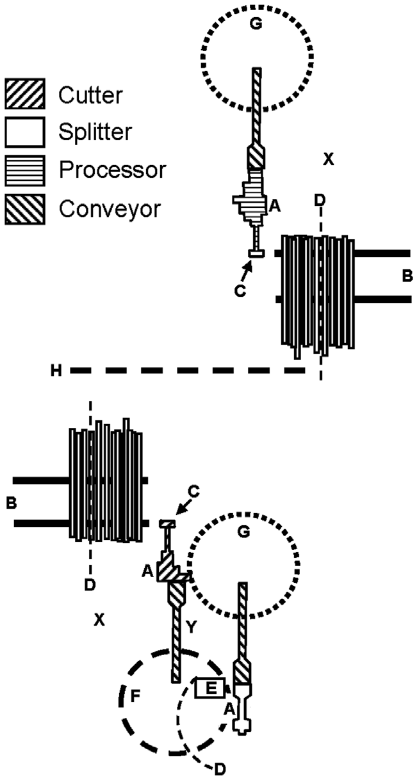

Fig. 1. Organisational overview of the firewood processing. A = operator's position during machine work; B = log loading table; C = loading roll; D = outer border of a demarcated 2 m area; E = chunk table (1.1 × 0.8 m, height 0.3 m); F = chunk pile; G = billet pile; H = tarpaulin; X = observer's position during cutter and processor work; Y = observer's position during splitter work. Note that both machine systems were used at both work stations and that only cutter or splitter was in position simultaneously.

wooden beams, placed 1.65 m apart and perpendicular to the machine (Fig. 1), held the logs at a height of 0.54 m above ground. To load machines, operators were required to vertically lift logs to the level of machines' loading roll (0.99 m). Loading rolls were placed in line with the closest beam, at a horizontal distance of 0.47 m (Fig. 1). The distance between the machine's operating position and the log loading table was 1.9 m. For logistic reasons, the splitter always succeeded the cutter and was placed on a standardised location in relation to the cutter's work place (Fig. 1). The splitter was not moved during its work shifts, so the proximity to the log chunk pile depended on the pile's size; i.e. the operator's preceding production with the cutter. The centre of the pile was 1.8 m from the machine operating position and the initial distance to the pile was <0.5 m.

The study was conducted on 91.9 m³ solid birch (*Betula* sp.) wood, bark included. The logs (n = 2199) were mechanically harvested and processed for pulp wood requirements. The logs' diameter on bark at the top end was >5 cm, their lengths were between 2.0 and 6.0 m, and the width of crooks did not exceed the log's largest diameter by more than 30 cm. Prior to the study, logs were marked with individual numbers and their root and top diameter on bark and length were recorded. Logs were considered to be conical frustums, with volume

$$V = \pi \times L \times (R^2 + r^2 + R \times r) \times 3^{-1} \quad (1)$$

where R and r are the root and top radii of the log, respectively, and L is the length (Hazewinkel 1988). Logs were sorted into three groups according to their root diameter on bark (Table 3). To allow them to be handled, logs in the group with the largest root diameter were cut to lengths in the interval 2.00–2.50 m. Logs in the other groups were not cut. Logs in the medium root diameter

Table 3. Characteristics of logs by wood class.

Wood class	Number of logs	Root diameter (cm) Interval	Root diameter (cm) Mean (SD)	Length (m) Mean (SD)	Volume on bark (m³) Mean (SD)	Volume on bark (m³) Total
1	925	13.0–17.9	14.9 (1.4)	4.49 (0.50)	0.054 (0.013)	49.8
2	1042	7.0–12.9	10.9 (1.3)	4.08 (0.51)	0.027 (0.008)	27.7
	232	18.0–30.0	20.4 (2.1)	2.46 (0.11)	0.062 (0.013)	14.4

group constituted wood class 1, while the logs in the smallest and largest root diameter group were put together in a ratio of 5 : 1 to constitute wood class 2. The variation in mean log volume within wood classes, described as the coefficient of variance (CV), differed significantly between wood classes 1 and 2 ($T = 19.9$, $p < 0.001$), as expected. The CVs were, respectively, 23.9% (SD 3.0%) and 49.0% (SD 5.4%) for wood classes 1 and 2, with no significant differences between systems ($T \leq 1.75$, $p \geq 0.097$). The mean log volume for work shifts were, respectively, 0.0538 m³ (SD 0.0015 m³) and 0.0338 m³ (SD 0.0028 m³) in wood classes 1 and 2, with no significant differences between systems ($T \leq 1.65$, $p \geq 0.191$). Mean log volume was tested as a covariate in the models of Analysis of Variance (Eq. 3, below) but did not contribute significantly neither in the full nor in the truncated model ($p = 0.320$ and 0.054, respectively) and did only increase the level of explained variance (r^2) by one percent unit. Therefore, the mean log volume within wood classes was considered equal between systems and operators. The logs had a raw density of 851 kg m^{-3} (SD 41 kg m^{-3}, $n = 958$), a moisture content of 41.7% (SD 2.2%, $n = 240$) and were frozen during the study. There was no significant difference in raw density between wood classes ($T = 0.80$, $p = 0.422$).

Before each work shift, logs were loaded on the log tables to a stack height of 0.5–1.5 m. The root ends of the logs were always oriented towards the machine and processed first. Split wood was removed after both processor and splitter work shifts, and after the latter remaining wood chunks were collected. Chunks were considered to be cylinders and their length and middle diameter were measured for volume calculations. Since the sawblade's cutting width was 6 mm and a cut was assumed every 30 cm along the logs expressed as conical frustums (Eq. 1), 1.84% (SD 0.07%, $n = 1337$) of the log volume was calculated to be transformed to sawdust. To give valid spitting production figures, remaining chunks' volumes were, hence, increased by 1.9% ($1 \times (1 - 0.0184)^{-1} \times 100$) before being deducted from cutting production.

Prior to each work shift, operators were told to work at their own pace and were given instructions regarding safety and standardised work routines (to process one log or chunk at a time and to move a new supply of logs or chunks into the demarcated two-metre area on the log loading table or around the splitter when the area was empty; Fig. 1). The chunk length was set to 30 cm and all wood chunks were to be split, with the maximum acceptable size of billets corresponding to a quarter of a cylinder with a diameter of 20 cm (0.0047 m³). Only pieces larger than the maximum size were to be re-split. Operators had a maximum-sized example billet within sight during work shifts. Operators worked under active supervision for 5–10 min prior to each shift. During work shifts, a researcher observed the work from a position located diagonally behind the operators (Fig. 1). The observer corrected unsafe behaviour, violations to standardised work routines and helped to correct machine malfunctions. Two observers were used, each assigned to the same operators throughout the study.

Time consumption for the work was recorded through continuous time studies by the use of Husky FS3 hand-held computers running Siwork 3 version 1.1 software (Kofman 1995). The time consumption was recorded as work time (WT), which was transformed for analysis to main work time (MW) (IUFRO WP 3.04.02 1995) in minutes per m³ solid wood on bark (min m^{-3}). WT and MW correspond approximately to the E_{15} and E_0 time, respectively. Study units for the cutter and processor were logs and for the splitter the study unit was 50 split wood chunks, the latter chosen for data entry reasons. Work elements (Table 4) did not overlap and thus, no priority order was assigned.

Through snowball sampling, the 12 operators were selected to compose a homogenous group of males with recurrent annual experience of processing more than 10 m³ of solid firewood with a circular saw cutter and hydraulic splitter. Grounds for excluding candidates were smoking, restraining physical conditions and recurrent annual experience of processing firewood volumes exceeding 50 m³ per year or of work with a firewood processor. Operators' mean (SD, interval) age, height and mass with clothes and shoes was 69.6 years (5.5, 60–79), 1.73 m (0.06, 1.65–1.85) and 79.9 kg (5.2, 70.9–90.2), respectively. Prior to the study, operators were asked about their motivation for their routine firewood

Table 4. Definition of work elements.

Work element	Applies to	Definition
Loading	Cutter & processor	Transport of logs from log table to machine. Started when operator moved from the machine towards the log table and stopped when machine work started.
Machine work	All machines	Wood processing, including de-jamming of conveyor. Cutter and processor: started when operator began to push the loaded cutting cradle towards the sawblade and stopped when loading started. Splitter: included both loading and splitting wood chunks.
Miscellaneous	All machines	Other activities that contributed to work, e.g. moving logs or chunks closer and picking up billets from ground.
Delays	All machines	Operational, mechanical and personal delays that interrupted normal productive work activities.

processing, which yielded a high mean score: 7.1 (SD 1.6) on a 10-grade scale, where 10 was the highest possible motivation for the work.

Operators' heart rates were recorded every 15th second during work shifts with cordless heart rate monitors (Polar Electro Oy, Finland). The monitors showed no indications of interference by the machines' electrical engines. Before work on the operators' second day their heart rate at rest was recorded after they had lain down for at least 20 minutes. No coffee or other sustenance was offered prior to the rest heart rate recordings. The physical workload was described as the percentage of the heart rate reserve (HR_{res}) used and calculated as

$$HR_{res} = (HR_w - HR_r) \times (HR_m - HR_r)^{-1} \times 100 \qquad (2)$$

where HR_w is mean heart rate during work and HR_r is heart rate at rest (Rodahl 1989, Wu and Wang 2002). HR_m is maximum heart rate and was estimated as $HR_m = 210 - (0.662 \times \text{age})$ (Bruce et al. 1974).

Deviations were expected, but unwanted, variations in the normal work procedures, and thus not included in the work element Delays. Deviations were counted, divided into the categories re-cuts, re-splits, external disturbances and human disturbances. Re-cuts occurred when logs with sizes exceeding the saw blades' cutting capacity (23 cm) were treated. When logs had to be cut several times to separate a chunk despite having a small diameter, due for instance to crooks, each extra cut was considered to be an external disturbance. Re-splits occurred when billets had to be re-split after a well-performed splitting of a large diameter (>20 cm) chunk. In cases when operators re-split billets that according to the observer did not need to be re-split to meet the target size, the cases were nevertheless counted as re-splits. Each re-splitting of a billet was counted, so the perfect splitting of a large chunk could be succeeded by, for example, four re-splits. Unsuccessful splitting of a chunk of appropriate diameters (<20 cm) was counted as an external disturbance. Other external disturbances were those considered to be caused by the machinery (e.g. the conveyor jamming or a splitting axe malfunctioning) or the wood, while human disturbances were those considered to be caused by the operator (e.g. inappropriate machine commands). An analyse based on deviations per produced m^3 is presented here, while the deviations are further described and analysed differently elsewhere (Lindroos, in prep.).

Directly after each work shift, operators were individually interviewed about their experiences during the work. Each interview included the same questions, which had been introduced before each operator's first work shift. Operators were asked to report their perceived level of physical exertion, efficiency, motivation, risks and deviations during the normal work on a Borg CR100 scale with instructions adapted from Borg (1998). Borg's Category-Rate scales are suitable for measuring the intensity of most types of experiences (Borg 1998) and the CR100 scale ranges from 0 to 100 in centiMax (cM) units, with descriptive adjectives that correspond to certain numbers on the scale (Borg and Borg 2002). The scale's main anchor is at the number 100 (adjective "Maximal"), which represents the strongest previously experienced intensities. However, the scale allows operators to report higher values than 100. The interview also contained questions concerning perceived causes of deviations, desired changes in the work, perceived risks and whether the operator would like to work in a similar fashion at home. Operators were told not to discuss the study with each other.

The method used to analyze effects of treatments was Analysis of Variance (ANOVA), based on the model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + c_k + (\alpha c)_{ik} + (\beta c)_{jk} + e_{ijk} \quad (3)$$

where y_{ijk} is the response variable, μ is the grand mean, α_i is the fixed effect of system, β_j is the fixed effect of wood class, c_k is the random effect of operator and e_{ijk} is the random error. The model also contains the fixed interaction effect $(\alpha\beta)_{ij}$ and the two random interaction effects $(\alpha c)_{ik}$ and $(\beta c)_{jk}$. In the cases where $n = 12$ and there were no significant interaction effects with operator, those interaction effects were removed from the model (truncated ANOVA) to improve otherwise low degrees of freedom in the analysis of operator as main effect. When evaluating the component machines of the systems the same model (Eq. 3) was used, but with β_j signifying the fixed effect of machine instead of system. Due to their dependency to treatments, it was not possible to use observed exertion or perceptions of work as co-variates to the model.

A general linear model (GLM) was used for analyzing the ANOVA models (Minitab 14, Minitab Ltd.). During the GLM procedure, pairwise differences were analysed with Tukey's simultaneous test of means. This procedure allowed analyses of differences between e.g. system/machine and wood class combinations while considering the operator blocking. Analyses of Pearson's correlation coefficient were used to find variable relationships, which were established through linear regression analysis. The critical significance level was set to 5%.

3 Results

The total study time was 108 hours and 50 minutes, of which 57.3 min (0.9%) consisted of delays. The machine that caused most delays (2.1 ± 3.4% of work time (mean ± SD)) was the cutter, mainly due to problems with its movable blade cover, while delay times for splitter and processor were minor (<0.5 ± 0.7%). Delay times were deducted from the time consumption and were not included in the further analyses.

3.1 Systems' Efficiency

The three main effects system, wood class and operator significantly affected the time consumption (truncated ANOVA, $p \leq 0.001$), which not was true for the interaction effect of system and wood class ($p = 0.479$). Work was conducted more efficiently with system *proc* than with system *cut-split* and wood of class 2 required more work time than wood of class 1 (Fig. 2). When considering operator blocking, the time consumption for the four combinations of systems and wood classes were significantly different, (Tukey test, $p \leq 0.007$; Fig. 2). Within operators, the mean time consumption per m³ with system *proc* expressed as a ratio of the time consumption with system *cut-split* was 0.67 (SD 0.10) and 0.75 (SD 0.13) for processing

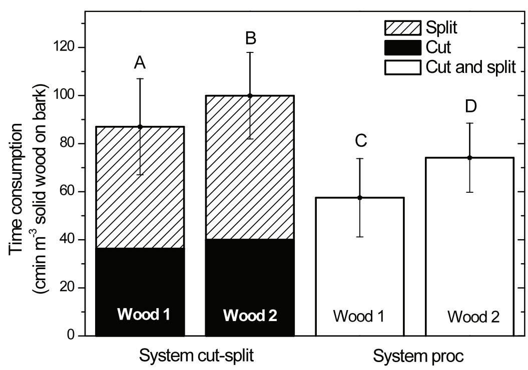

Fig. 2. Time consumption (mean and SD between operators, n = 12) by system and wood class. Different letters indicate significant differences (p < 0.05) between combinations with consideration taken to operator blocking (Tukey test).

Table 5. Number of deviations per m³ solid wood on bark processed (mean and SD over operators, n = 12) and the simple linear regression function (y = a + b × x) for the relation between deviations (x, n m^{-3}) and time consumption (y, min m^{-3}).

System	Extra work Re-cuts	Extra work Re-splits	Disturbances External	Disturbances Internal	Deviations, Total	Regression variables a	b	p	r^2
Wood class 1									
Cut-split	0.5 ^{a} (0.7)	8.8 ^{a} (7.7)	90.9 ^{a} (32.5)	9.2 ^{a} (14.1)	109.5 ^{ab} (44.5)	55.8	0.29	0.027	0.40
Proc	0.3 ^{a} (0.6)	3.0 ^{a} (2.8)	65.0 ^{a} (47.8)	8.9 ^{a} (5.9)	77.2 ^{b} (48.5)	33.3	0.31	<0.001	0.88
Wood class 2									
Cut-split	0.6 ^{a} (1.2)	32.7 ^{b} (18.9)	90.2 ^{a} (28.4)	9.4 ^{a} (8.5)	132.8 ^{a} (40.8)	65.5	0.26	0.044	0.35
Proc	1.0 ^{a} (1.4)	30.9 ^{b} (21.8)	78.1 ^{a} (39.8)	12.4 ^{a} (7.5)	122.3 ^{a} (47.5)	55.0	0.16	0.084	0.27

Within columns, different superscript letters indicate significant differences (p<0.05) between system and wood class combinations with consideration taken to operator blocking (Tukey test).

wood of classes 1 and 2, respectively. The mean time consumption for processing wood of class 1, as a ratio of the time required for wood of class 2, was 0.87 (SD 0.08) and 0.78 (SD 0.18) using systems *cut-split* and *proc*, respectively. Within-operators, the relative difference between systems did not vary between wood classes (Paired T-test, $p=0.158$), nor did the relative difference between wood classes differ between systems (Paired T-test, $p=0.218$). Age was not correlated to time consumption in any of the four system-wood class combinations ($p \geq 0.070$).

Mean volume of produced billets differed significantly between operators, systems, wood classes and there was an interaction between the two latter (truncated ANOVA, $p \leq 0.042$). When working with system *proc* and wood class 2, operators produced billets with a significantly (Tukey test, $p \leq 0.004$) lower mean volume of (0.91 ± 0.38 dm³ (mean ± SD), n = 239) than with the other three combinations of system and wood class (1.04 ± 0.42 dm³, n = 719). The mean length of the billets was 31.1 cm (SD 2.0 cm) and besides the operator effect (truncated ANOVA, $p=0.001$) there were no significantly treatment effects (truncated ANOVA, $p \geq 0.104$). Changing the factor "operator" to fixed instead of random in the truncated ANOVAs allowed tests of the amount of operators with different billet sizes, which was indicated as low; one operator significantly differed in volume of produced billets from one other operator (Tukey test, $p=0.043$) and in chunk length from three other operators (Tukey test, $p \leq 0.013$).

3.2 Systems' Deviations from Normal Work

The number of deviations from normal work per m^3 processed were significantly affected by wood class and operator (truncated ANOVA, $p \leq 0.011$), and the system's effect was just outside the set level of significance ($p=0.058$). Re-splits were more frequent when class 2 wood was processed, irrespective of system (Table 5). The most common kinds of deviation were external disturbances (Table 5), of which high proportions were due to chunks and billets jamming the conveyor and malfunctions of the splitting axe. Deviation frequency was correlated to time consumption, but the level of explained variance was generally low except for the combination of system *proc* and wood class 1 (Table 5). At the machine level, irrespective of wood class, work with the cutter resulted in significantly fewer deviations per m³ (Tukey test, $p=0.001$) than work with the other machines (data not shown).

3.3 Machines' Efficiency

Due to the operators' effect on time consumption, it was important to investigate differences between operators' work in the study. For this purpose, the operator differences for each of the component machines of the systems were evaluated. No significant interaction effects between operator and machine or wood class were found (full ANOVA, $p \geq 0.126$) for neither of the variables analysed in Table 6. Machine, wood class, operator and the interaction effect between

Table 6. Levels of significance (p-values) from the analysis of variance of treatment's effect on time consumption (min m^{-3} solid wood on bark), used heart rate reserve (%) and perceived (Borg CR100, cM) efficiency, exertion, motivation and risk. Error DF = 55

	Machine	Wood	Operator	Machine × Wood	r^2
Time consumption	**<0.001**	**<0.001**	**<0.001**	**0.011**	86.8%
Used heart rate reserve	**0.002**	0.260	**<0.001**	0.807	81.0%
Perceived efficiency	0.170	0.492	**<0.001**	0.095	57.0%
Perceived exertion	0.380	0.112	**<0.001**	0.810	47.1%
Perceived risk	**0.037**	0.140	**<0.001**	0.176	64.0%
Perceived motivation	**0.010**	0.934	**<0.001**	0.799	68.8%

Significant values ($p < 0.05$) in bold.

Table 7. Mean time consumption and time distribution between work elements (mean and SD) between operators (n = 12).

Wood class	Machine	Time consumption (min m^{-3})	Work element (%) Loading	Machine work	Miscellaneous
1	Cutter	36.2 ^{a} (7.4)	26.5 ^{a} (3.2)	70.4 ^{a} (2.4)	3.1 ^{abc} (3.2)
	Splitter	50.6 ^{b} (13.9)	n.a.	95.5 ^{b} (1.7)	4.5 ^{b} (1.7)
	Processor	57.5 ^{bc} (16.9)	17.3 ^{b} (3.2)	79.6 ^{c} (3.6)	3.1 ^{abc} (2.3)
2	Cutter	39.9 ^{a} (7.3)	29.2 ^{a} (2.9)	67.3 ^{d} (1.9)	3.5 ^{abc} (2.4)
	Splitter	59.9 ^{c} (11.2)	n.a.	96.9 ^{b} (1.9)	3.1 ^{abc} (1.9)
	Processor	74.2 ^{d} (14.4)	16.9 ^{b} (3.1)	81.3 ^{c} (2.7)	1.8 ^{c} (1.0)

n.a. = not applicable. Different superscript letters within columns indicate significant differences ($p < 0.05$) with consideration taken to operator blocking (Tukey test).

machine and wood class all had significant effects on time consumption per m³ processed (truncated ANOVA, Table 6). The cutter required the least time, irrespective of wood class (Table 7) (Tukey test, $p \leq 0.007$). For splitter and processor, wood of class 2 required significantly more time per processed m³ (Tukey test, $p \leq 0.030$). Within machines, wood classes had little influence on the time distribution among work elements. The 3% higher proportion for loading wood of class 2 than for loading wood of class 1 when using the cutter was the largest wood class effect.

The operators' mean heart rate during the work shifts was 98.0 beats per minute (SD 18.7, interval 70–135), corresponding to 35.3% (SD 12.9%, interval 12–68%) of their heart rate reserve, with significant differences both between machines and between operators (Table 6). Within operators and regardless of wood class, operators used more of their heart rate reserve when working with the cutter (38.9 ± 14.5%, mean ± SD) than when working with the splitter (33.3 ± 11.5%) or processor (33.8 ± 12.2%) (Tukey test, $p \leq 0.009$). Used heart rate reserve was not correlated to time consumption in any of the six machine-wood class combinations ($p \geq 0.108$).

3.4 Operators' Perceived Efficiency, Exertion, Risks and Motivation

The operators reported that they were very content with the efficiency of the machines and the work methods (50.5 ± 19.0 cM) used in the study. Perceptions differed significantly between operators in this respect, but there was no effect of machine, wood classes or the combinations of machines and wood classes (Table 6). Between operators, there was no correlation between perceived efficiency and time consumption per m³ processed in the different machine and wood class combinations (Pearson's $r = -0.48$ to 0.46, $p \geq 0.118$).

The operators generally perceived their levels of exertion to be moderate to strong during the work (36.0 ± 14.7 cM), with differences between operators being the only significant effect (Table

6). Between operators, the splitter and processor with wood class 1 were the only combinations with a significant correlation between operator's used heart rate reserve and perceived exertion (Pearson's $r = 0.61$, $p = 0.03$), but even in these cases the level of explained variance was low (simple regression, $r^2 = 0.38$).

Risk perceptions differed between operators and between machines (Table 6). The accident risks during the work were generally perceived to be very low. The splitter was perceived to be the least risky machine, (6.4 ± 5.2 cM) while the risk scores for the cutter and processor were slightly higher (9.6 ± 7.3 cM and 9.5 ± 7.8 cM, respectively). The differences within-operators were, however, just outside the set level of significant (Tukey test, $p \geq 0.057$). Operators reported strong perceived motivation for the work during the study, with an overall mean value of 52.5 cM (SD 20.1). However, perceived motivation levels differed both between operators and between machines (Table 6). Within operators and regardless of wood class, operators perceived significantly higher motivation during work with the splitter than with the cutter (Tukey test, $p = 0.008$) and no other significant differences were detected.

4 Discussion

4.1 Operator Influences

As expected, the more mechanised system (*proc*) was significantly more efficient than the other system. The efficiency was also higher when logs with a relatively high mean volume and relatively homogenous diameters (wood class 1) were processed, regardless of mechanisation level. Despite the homogeneity of the operatives in terms of demographic variables and work experience, large inter-individual variations in efficiency were found in the current study (Fig. 2) just as in numerous other studies (e.g. Hansson 1965, Björheden 2001, Ovaskainen et al. 2004). The quota between the most efficient and the least efficient operator's time consumption ranged from 1.66 for system *cut-split* in wood class 2 to 2.19 for system *proc* in wood class 1. With the least efficient third of operators removed from the material, time consumption values generally decreased by 10.5–17.6% on machine level. Despite the high age and the large span between operators, age was not correlated with efficiency in this study. This fact was probably due to the operators' voluntary participation. Persons with perceptions of declined ability for the work were unlikely to have agreed to participate, which may have masked some of the general effect of declining physical capacity with old age in the results.

The variations found between operators did not influence the results in terms of significant interaction effects, for instance between operator and system or machine. In other words, operators all responded similarly to treatments, but at different absolute levels. Hence, the current study's finding of a 33% lower mean time consumption for system *proc* compared to system *cut-split* when processing wood of class 1 is probably more applicable to other operators than the absolute mean time difference of 29.5 min m^{-3}. However, for operators that differ greatly from the studied group in terms of demographic variables and work experience, the differences are also likely to distort relative comparisons. Interestingly, operators' perceptions of the work varied more than the observations of performed work.

Operators had little experience of using the specific machines prior to the study, even though they had extensive experience of the *cut-split* system. Despite that work elements were similar in many aspects, processor was a type of machine that they had little or no experience of, since this was a selection criterion in the formation of a homogeneous group. It is possible that a certain learning effect may have influenced the results, reducing time consumption per m^3 as the time the operators spent working on the machines increased. On the other hand, it has been argued that operators perform above their normal level when studied, especially during the first days (Makkonen 1954, Harstela 1991). These factors may therefore have had counteracting effects on changes in the operators' performance over time during the study. Furthermore, any learning influence on the results was probably minor due to the similarities and relative simplicity of the machines and work tasks, the training time before each shift (5–10) minutes and the high number of work cycles performed during each work shift.

The possibility of learning effect suggests, however, that the efficiency differences between the two systems probably would increase with further work time on the processor.

4.2 External Validity

The finding that the time required to process a unit volume of wood was lower in a more mechanised system is consistent with previous studies' findings (cf. Table 1). As mentioned previously, between-study differences in absolute values of time consumption are difficult to compare meaningfully, because of differences inter alia in methodology, conditions and targeted billet properties. However, the following comparisons with similar machines and systems illustrate both some of the differences and the difficulties involved in making comparisons.

A *cut-split* system studied by Swartström (1986) reportedly had 60% lower time requirements for processing wood approximating to class 1 than the values obtained in the current study. However, in the cited study 25 cm long billets were produced, the work involved in loading logs on the machine was excluded and the time consumption values were based on the processing of four three-metre logs. A blade cutter study by Liss (1996) yielded a similar time consumption value (36.7 min m^{-3}) to those found in the current study (36.2 and 39.9 min m^{-3} for wood classes 1 and 2, respectively) when producing 35 cm long billets. The time consumption values were based on eight operators' processing a total of 8 m^3 of logs in mixed, but unspecified diameters. In a processor study by Björheden (1989) time consumption values 50% lower than those found in the present study were obtained, but longer billets (50 cm) were produced, only a small amount of wood (0.8 m^3) was processed and there was only one operator. A study by Granqvist (1993) reportedly found that operation of an investigated processor consumed less than half as much time (24.2 min m^{-3}) as found in the current study, based on a sample of two operators processing 2.5 m^3 of wood into 35 cm long billets.

Generally, previous studies have found that less time is required per m^3 processed wood than the current study. The study's external validity is nevertheless considered strong, since differences are likely to be mainly attributable to the differences in study design and operator characteristics. A small number of logs were processed in most previous studies, implying that operators could work harder than normal without becoming exhausted during the experiment (Makkonen 1954, Harstela 1991). In the present study, work was conducted during relatively long (1.5 h) work shifts at levels that are generally recommended for continuous work (25–40% of one's workload capacity (Rodahl 1989, Wu and Wang 2002)). Furthermore, considerably fewer operators were included in the previous studies (≤8) and they were younger (≤59 yrs) than in the current study. The physical restraints of high age as well as the psychological and physical restraints of long work shifts were likely to decrease work pace compared to other studies. The current study is, therefore, believed to better reflect productivity levels during the operators' normal use of the machines, while most previous studies mainly indicate maximum productivity levels.

4.3 Deviations

Despite considerable inter-individual differences in time consumption and frequency of deviations from the planned production processes (e.g. errors and malfunctions) between operators, the two variables were positively correlated (Table 5). The reasons for the differences in the frequencies of deviations between the two wood classes are to some extent debatable. However, the increased time requirements for processing wood of class 2 can be mainly ascribed to its lower mean log diameter. The increased number of logs that have to go through the machine for each m^3 processed is likely to contribute considerably to the number of deviations, but a relevant issue in this context that is less straightforward to address is whether they were generated solely by the machine, solely by the operator or by an interaction between the two. In addition, the larger variation in log diameter in wood class 2 probably contributed to deviations, since the splitting axes' height position was inherently adjusted to the preceding chunk's diameter. With given billet target properties, a large variation in diameter implies a higher proportion of unsuccessful splitting operations. For similar reasons sawmills generally sort logs carefully by diameter to avoid deviations from targeted lumber. The frequency of deviations per processed m^3 appears to be associated with a certain amount of extra time, to be added to a base time for deviation-free work. Consistently, the efficiency expressed as number of work cycles per work shift decreases with increased number of deviations for splitter and processor (Lindroos, in prep.). For cutter, on the other hand, the deviations are positively correlated to the number of work cycles, and do not influence the efficiency as suggested (Lindroos, in prep.). To further elucidate this matter, attention should be paid to the time consumption associated with individual deviations.

Mechanisation often implies more complex operations and thus, possibly, higher sensitivity to deviations. The current study did not provide any support for such a correlation, since there were fewer deviations with system *proc* per m^3 than with system *cut-split*. However, large proportions of deviations were due to poor performance of the conveyor, which affected system *cut-split* twice as often as system *proc* because conveyors were used twice rather than once. Excluding those deviations may have yielded the expected correlation. Additionally, other observations indirectly supported the expected sensitivity increase with mechanisation. The mean volume of the produced billets was significantly smaller for the combination of system *proc* and logs with great variation in diameters and volumes (wood class 2). This can be deducted to the system *proc*'s design, which rendered less operator control over splitting performance and thus signified a narrower span of raw material properties that allowed a desired outcome. The difference is logic in the sense that efficiency is generated on the expense of versatility.

4.4 Economic Considerations

If time is a limiting factor in a processing situation, a system will need to match or exceed a specific efficiency to meet a given production target. If the production target is to process 30 m^3 of solid wood and 40 h is available, system *proc* would meet the requirements but system *cut-split* would not. In leisure time based, small-scale firewood processing such strict schedules are believed to be rare. A more realistic approach for investment analyses would be to focus on saved work time, which also provides a basis for economic comparisons between systems. According to this study, 30 m^3 of wood of class 1 would be processed 14.7 h faster using system *proc* than using system *cut-split*. If the system is calculated to be used for 10 years, the time saving would amount to 147 h. Disregarding interest rates and machine salvage values, the extra cost per saved hour would be the purchase difference (1006 €, Table 2) divided by the calculated time savings, which would result in an extra cost of 6.8 € h^{-1}. The equivalent extra cost for processing wood of class 2 would be 7.9 € h^{-1}. The investor would then have to assess whether the extra cost is acceptable, i.e. assess the value of the extra leisure time. The less time that is available, the higher extra cost the investor is likely to accept.

The presented analysis builds on the same concept as Gullberg's (1991) comparisons between self-employed forest work and hiring a contractor for the work, but from a reversed approach. The reversed approach is required for analysing the competitiveness of more efficient and more expensive equipment for a given production quantity during leisure time. The equivalent situation in Gullberg's (1991) analysis would be if a forest owner for whom it would be economically advantageous to do work him/herself, would nevertheless decide to hire a contractor in order to gain free leisure time.

Finally, it can be concluded that a relatively small increase in the mechanisation level of firewood processing can increase efficiency considerably. However, whether or not the increase justifies the extra cost for an investment in equipment used for self-sufficiency purposes is dependent on production volumes and the potential investor's valuation of extra leisure time. Additional considerations are also likely to affect investment decisions, such as perceptions of outcome quality, ergonomic factors and safety.

Acknowledgement

This study was conducted within the FOR-programme, which addresses self-employed family forestry's working conditions. The work was financially supported by the Faculty of Forest Sciences of the Swedish University of Agricultural Sciences, the SLO foundation's grant SLO-892, Interreg IIIA in the Kvarken-MidScandia region and Baltic forest – an Interreg 3B project. Lennartfors AB and Norra Skogsägarna kindly provided testing material. Thomas Hörnlund, Urban Johansson, Tony Knif, Christer Hedegård and the Regional Forestry Board of Västerbotten are thanked for enabling the field work. Pär Lindroos is especially thanked for invaluable assistance in the field study. Thanks are also due to Sören Holm for statistical advises, to Tomas Nordfjell, Gun Lidestav, Dag Fjeld, Stefan Söderfjell and Börje Rehn for valuable comments and to Sees-Editing Ltd. for revising the English.

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