

Article

Influence of Chain Sharpness, Tension Adjustment and Type of Electric Chainsaw on Energy Consumption and Cross-Cutting Time

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Abstract: Recently, electrical cordless chainsaws were introduced, which provide less harmful working conditions for the operators, and should therefore be deployed as much as possible in all non-professional and professional applications. The low power of the electric engines may result in lower efficiency and higher energy consumption in the case of over-tensioned chains, due to increased friction between the saw and the chain. Therefore, a partial factorial experiment with one factor on three levels (saw type) and two factors on two levels was designed, whereby a wooden beam was cross-cut at two levels of chain sharpness and tension. The time of cross-cutting and energy consumption were controlled. The chain tension does not have a significant effect onto time of cross cutting, or electricity consumption. Both have cross-cutting and energy consumption have been found to differ significantly when comparing the saws used in the experiment. The average efficiency of cross cutting using electrical chainsaws reported is 2.35 times lower than when using petrol powered saws. The lower efficiency is caused by the lower engine power of electrical saws, and lower speed of chain rotation. Energy consumption and time of cross cutting are significantly higher when using a blunt chain, with large differences in time of cross cutting and electricity consumption, making the chain sharpness the most important of all controlled factors. In the study, we did not find evidence that over tensioning of the chain increases the time of cross cutting or energy consumption, however the integration of such systems is recommended because of the worker's safety.

Keywords: forestry; forest operations; wood harvesting; electric tools; cutting efficiency; electric cordless chainsaw; cross cutting; sharpness; energy consumption; tension

1. Introduction

Forests are supplying the world with almost 3.97 billion m³ of wood annually [1,2]. Due to its intrinsic qualities and general versatility [3], wood has immensely valuable to humanity since the earliest prehistoric times [4]. Today, most wood is supplied from natural, planted forests and plantations [5].

In recent years, the stagnant oil prices [6] and the uncertainty in the wood market, which is experiencing major structural changes [7], have caused a renewed drive for efficiency in forest operations. Most new plantations and the majority of world forest resources are based in developing countries [8], where the specific socio-economic conditions (e.g., availability of low-cost rural labour) have favored the use of manual or semi-mechanized forest harvesting work techniques [9]. The mechanization of forest operation should be the ethical imperative of any modern society, as it offers great benefits

in terms of worker safety, operator comfort, and general efficiency [10]. Still, the transition from manual or semi mechanized work to full mechanized operation is a treacherous journey, as it requires specific skills and large capital investments. One of the best solutions is a steppingstone approach whereby semi-mechanized, low-investment systems are used as transitional technologies towards fully mechanized technologies [11]. In almost every transitional harvesting system, however, there is the need for semi mechanized technology. This is a flexible, robust, and cost-effective work system, but also a dangerous one. Risks are mostly due to two reasons. The first one is the inherent danger of the activity, as the operator works outside a protective cabin, exposed to danger and weather, culminating in the highest accident rate in professional and non-professional work [12–15]. The second reason is the danger of the work tool itself [16]. In this regard, exposure to wood dust and exhaust fumes [17] and to noise and hand-arm vibration (HAV) are the main problems. The latter are the reason for the high frequency of hearing impairment [18] and vascular disorders (white fingers) among forestry workers [19].

Recently, electrical cordless chainsaws were introduced in the market. These devices cause a significantly lower exposure of the worker to noise, and eliminate the problem of fume inhalation, leading to less harmful working conditions for the operators. Due to these benefits, such tools should be deployed as much as possible in all non-professional and professional applications. In the latter case, however, there are important downsides that may limit electric chainsaws application, such as low battery duration, that requires the use of several batteries for normal work [20], but also lower power and efficiency in comparison to petrol powered chainsaws. At the moment, the harvesting of plantation forests seems to be the only viable professional application for these novel tools due to the smaller and more homogeneous tree dimensions that open the possibility to use lighter chainsaws [21,22].

The cutting efficiency and energy consumption of chainsaws are mostly influenced by the chain type, sharpness, and tensioning. In the case of harvester chains, it has been established that the cutting process has a significant effect on machine productivity, as it comprises up to 11% of effective work time, and there is a significant correlation with work quality [23]. Furthermore, due to importance of proper chain tensioning, automatic chain tensioning systems are installed as a standard in the harvester industry. Furthermore, brand new harvester chains have been found to vary significantly (6%) in terms of cutting time and energy consumption [24]. In the case of motor-manual felling, it has been established that the use of a chainsaw comprises 30%–65% of productive work time [25] and that a sharpened chain increases cross cutting efficiency [26]. Additionally, it has been recommended that chain tensioning should be automatized [27]. Despite such recommendations, chainsaws with an automatic tensioning system are rare. This can be attributed to the low price of the machine and the fact that operators are used to manual chain tensioning. Previous experiences in field studies with battery powered chainsaws highlighted that the relative low power of the electric engines may result in lower efficiency and higher energy consumption in case of over-tensioned chains, due to increased friction between the saw and the chain. With the present study, we considered the feasibility of development of an automatic chain tension system from the perspective of energy consumption and time of cross cutting, while controlling the chain sharpening and chainsaw type.

2. Materials and Methods

2.1. Test Protocol and Chainsaw Characteristics

A freshly cut, first grade spruce log with no visible mistakes was used for the experiment. It was sawn into a square beam with a side of 0.2 m, on the day before the trial. The beam's dimensions correspond to ISO 7182:1996 in regard to the length of the saw bars used in the experiment. Initially, the beam was 4.2 m long, but in order to ensure homogenous moisture 0.2 m long sections were cut off on both sides of the beam and discarded. The remaining log was sawn into three sections, and the trial replications were then made on all 6 beam fronts, to make up for any internal differences in the log.

In the trial, three types of chainsaw were used and were equipped with the saw bars and chains recommended by the respective saw's producer (Table 1). The time of cross cutting, which is defined as time in which the saw cross-cuts the beam under full throttle, was determined with an analysis of a digital recording made using a handheld camera according to harmonized time-motion studies guidelines [28]. The saws' energy consumption was measured using electricity meter [29] and includes the consumption of the respective charger (Table 2). The cross cutting was made under the saw's own weight, without applying additional force.

Table 1. Properties of the chainsaws and supplementary equipment.

Manufacturer	Makita	Stihl	Husqvarna
Model	DUC353Z	MSA 200 C-BQ	536Li XP
Weight ¹	3.3 kg	2.9 kg	2.6 kg
Saw bar type	165201-8	Rollomatic E Mini	501 95 95-52
Saw bar length	35 cm	35 cm	35 cm
Chain type	531.291.652	Picco Micro 3	H38 Mini Pixel
Chain pitch	3/8"	1/4"	3/8"
Number of drive links	52	72	52
Chain type	20 m/s	18.8 m/s	20 m/s
Battery type	BL1860B	AP 300	Bli200
Battery capacity	6 Ah	4.5 Ah	5.2 Ah
Number of batteries	2	1	1
Charger type	DC18RD	AL300	QC500
Manufacturer city, country	Makita Corporation, Aichi, Japan	STIHL Holding AG & Co. KG Waiblingen, Germany	Husqvarna Group, Stockholm, Sweden

¹ Without batteries, saw bar and chain.

Table 2. Trial setup and number of replications per factorial combinations.

Saw Type	Chain Filling	Chain Tension	
		Normal	Overtensioned
Chain saw 1	Sharp	5 (2)	5 (2) ¹
	Blunt	5 (1)	
Chain saw 2	Sharp	5 (2)	5 (2) ¹
	Blunt	5 (1)	
Chain saw 3	Sharp	5 (2)	5 (2) ¹
	Blunt		

¹ (2)—number of crosscuts within one replication.

The chainsaw tensioning has to be done in a manner that the chain has to move freely through the bar, without any of the drive links being visible from the side of the bar. To achieve that, when setting the normal chain tension, a snap test was used, where tension is acceptable if the chain is elevated in the middle of the saw bar, and only three drive links are visible. When the overtensioned saws were prepared for trial the chains were weighed down by a 1190 g weight, while the rule of three visible drive links was still being considered. The weight used was in line with the saws' tensioning mechanism, as a higher weight could result in damage to the tensioning mechanism. Sharp chains are brand new, factory-sharpened chains recommended by the respective saw's producer. Blunt chains were prepared by pushing the working saw under full throttle into a bucket of quartz sand (granulation 1–2 mm) for 20 s [30]. After the procedure, the chain and all the saw parts were carefully cleaned of excess sand.

2.2. Experimental Design

The trial setup was designed as a partial factorial experiment with one factor on three levels and two factors on two levels (Table 1). Within every one of the five repetitions in the trial, two cuts of a

wooden beam are made to ensure sufficient battery discharge. During the trial we have realized that when testing blunt chains one of the saws was unable to cut the beam. We were forced to lower the number of cuts when using blunt chains from 2 to 1, therefore with 40 replications in the trial, 70 beam cross-cuts were made instead of the planned 90.

2.3. Data Analysis

The statistical analysis included descriptive statistics, Levene's test for equality of variances, and Student's *t*-test for determining differences in means. When determining the differences in cross-cutting time and energy consumption in regard to sharpening, the data obtained from one cut was multiplied by 2 as to model the time of actual cutting. For testing means, the *t*-test for unequal variances was used. For all analysis the program IBM SPSS Statistics, Armonk, NY.

3. Results

3.1. Chain Tension in Relation to Cross-Cutting Time and Electricity Consumption

The chain tension does not have a significant effect on the time of cross cutting ($t = 0.942$; $df = 28$; $p = 0.354$) or electricity consumption ($t = -0.075$; $df = 28$; $p = 0.941$). On average it took 27 s and 0.0136 kWh of electricity to cross cut a 400 cm² wooden beam twice (Figure 1).

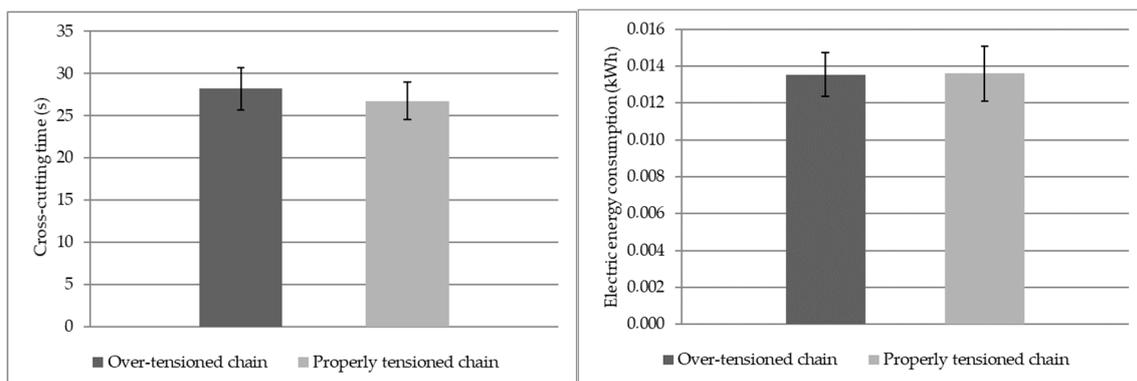


Figure 1. (a) Cross-cutting time consumption by chain tension adjustment—mean and 95% confidence interval (b) Electric energy consumption by chain tension adjustment—mean and 95% confidence interval.

3.2. Saw Type in Relation to Cross-Cutting Time and Electricity Consumption

The electricity consumption and cross cutting time are, however, significantly different when comparing the saws used in the experiment. The cross cutting with saw 3 took 23% and 32% longer than when using saws 2 and 1 (Figure 2), while the differences in cross-cutting time were statistically significant ($t_{2-3} = -4.587$; $df_{2-3} = 18$; $p_{2-3} < 0.000$; $t_{1-3} = -5.923$; $df_{1-3} = 18$; $p_{1-3} < 0.000$). There was no significant difference between, comparing saw 1 and 2 ($t_{1-2} = -1.699$; $df_{1-2} = 18$; $p_{1-2} = 0.107$).

The consumption of electricity between saws was highest when using saw 2, with the consumption being 22 and 35% higher for saw 1 and 3 respectively. Differences in electricity consumption between saws 2 and 1 and 3 were highly significant ($t_{1-2} = -3.222$; $df_{1-2} = 18$; $p_{1-2} < 0.005$; $t_{1-3} = 6.438$; $df_{1-3} = 18$; $p_{1-3} < 0.000$), while the difference between saws 1 and 3 was not significant ($t_{1-3} = -1.724$; $df_{1-3} = 18$; $p_{1-3} < 0.102$).

Electricity consumption was lowest with the saw that took the longest to cross cut the beam (Figure 2). Therefore, energy consumption efficiency (kWh/s) for all three saws was tested. Results show that there are significant differences in consumption efficiency between saws. Consumption of energy in relation to time of cross cutting with saw 3 is 31% and 39% lower than that of saw 1 and 2 respectively (Figure 3), with differences being statistically significant for saw 3 ($t_{2-3} = 8.327$; $df_{2-3} = 18$;

$p_{2-3} < 0.000$; $t_{1-3} = -4.660$; $df_{1-3} = 18$; $p_{1-3} < 0.000$), while no differences were observed between saws 1 and 2 ($t_{1-2} = -1.642$; $df_{1-2} = 18$; $p_{1-2} = 0.118$).

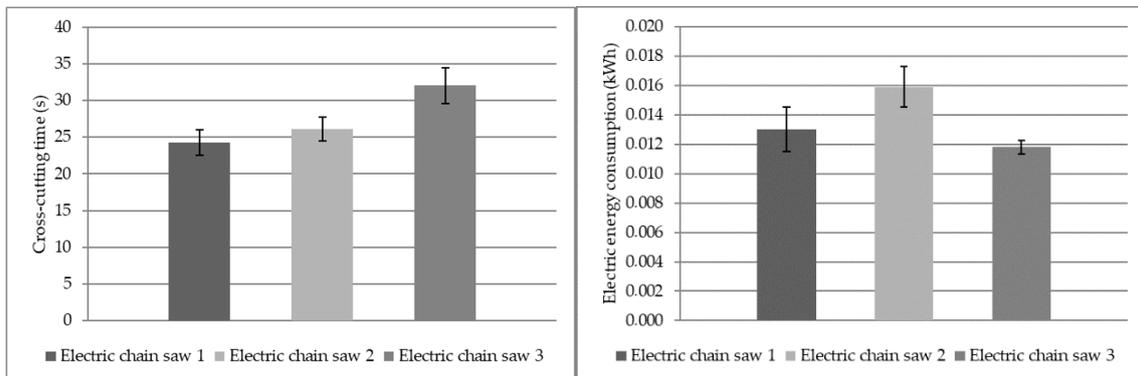


Figure 2. (a) Cross-cutting time and electric energy consumption by the type of electric chainsaw—mean and 95% confidence interval (b) Electric energy consumption by type of electric chainsaw—mean and 95% confidence interval.

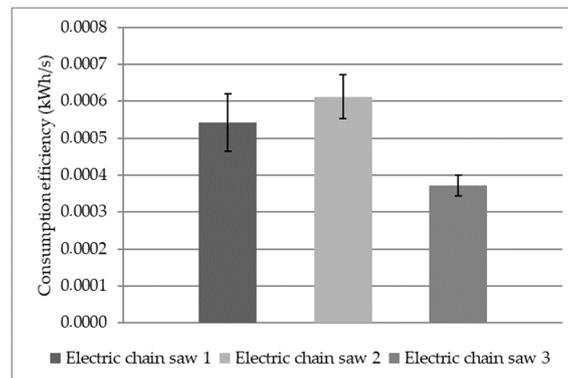


Figure 3. Efficiency of electric energy consumption by type of electric chain—mean and 95% confidence interval.

3.3. Energy Consumption in Relation to Cross-Cutting Time and Chain Sharpness

Energy consumption and time of cross cutting are significantly higher ($t_{OS} = -13.843$; $df_{OS} = 9.523$; $p_{OS} < 0.000$; $t_{SB} = -10.646$; $df_{SB} = 9.055$; $p_{SB} < 0.000$) when using blunt chain, with 6.2-fold difference in time of cross cutting and 6.7-fold difference in electricity consumption (Figure 4).

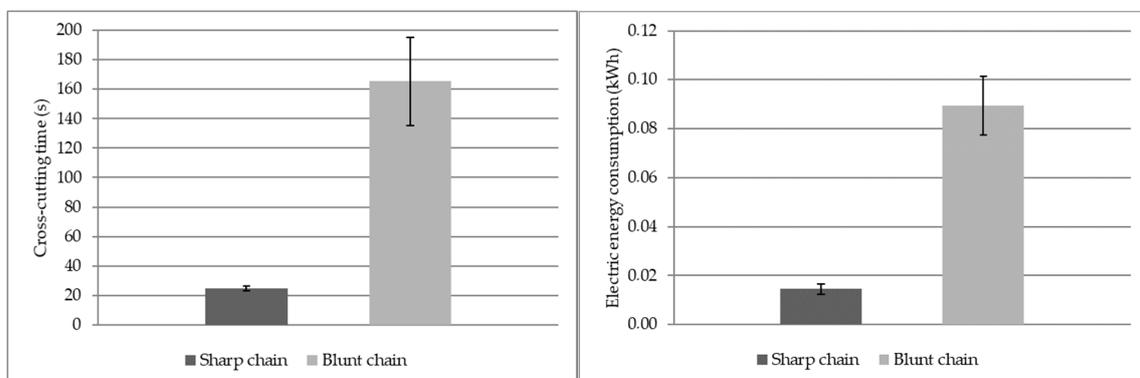


Figure 4. (a) Cross-cutting time consumption by chain sharpness—mean and 95% confidence interval (b) Electric energy consumption by chain sharpness—mean and 95% confidence interval.

4. Discussion

It has been established that chain tension has a non-significant effect on hand and arm vibration [31], and in the present research, a non-significant effect has been demonstrated for work efficiency and energy consumption. The hypothesis was based on the assumption that, due to the low power of the chainsaws' engines, the over tensioning of the chain will increase the friction between the saw bar and chain, therefore reducing the chain's speed, as observed by Gendek et al. [32]. However, the rejected hypothesis indicates sufficient power and torque of the saws for overcoming the additional friction caused by the over-tensioned chain. Furthermore, non-significant differences in the electricity consumption indicate that the energy required for overcoming the friction between chain and saw bar is low in comparison to the energy required for sawing wood. In regard to chain tensioning and cutting efficiency, previous research has demonstrated a significant effect in case of chain under-tensioning. In the latter case the lower friction between bar and chain causes the cutter teeth to wobble, thereby decreasing the effective time of cutting wood and with that the cutting efficiency [33]. Additionally, an undertensioned chain increases the kickback injury risk [27].

The average efficiency of cross cutting using electrical chainsaws ($29.13 \text{ cm}^2/\text{s}$) is 2.8 times lower than when using petrol powered saw Husqvarna 365 in forest [34], and 1.9 to 2.3 times lower when cross cutting with the Husqvarna 357XP in test conditions [33]. The lower cutting efficiency is caused by the lower engine power of electrical saws as, for example, the Makita DUC353Z has an engine with only 1 kW of power, whereas the petrol-powered saws from above references can produce 3.6 and 3.3 kW respectively. The second reason is the speed of chain rotation, that is lower in tested battery powered saws. The chain speed of battery powered saws is approximately 10 m/s lower than that of their petrol-powered counterparts, with reported speeds of 30.2 m/s and 28.5 m/s respectively.

The differences in cross cutting efficiency among saw types can be attributed to different engine powers, but also to differences in cutting parts of the saw, particularly the chain. Research shows that the efficiency of cutting depends on the chain type [26] and type of cutters [35]. Similarly, differences in energy consumption among saws can be attributed to differences in engine powers and torques [36]. We have concluded that the energy consumption is lowest when using the saw that had the lowest cross cutting efficiency, which is the consequence of slower cutting, whereby less power is being used. Research shows that the energy consumption of battery saws is two times lower than that of petrol saws [20], which is attributed to the efficient production of electricity, contrasted by the relative inefficiency of two stroke petrol engines, where reported engine efficiencies range from 17.98% to 29.2% [37,38], while at least 22% of fuel does not combust [39].

From all three controlled factors both efficiency of cross-cutting and energy consumption are most highly dependent on the chain sharpness, which is demonstrated by largest absolute differences in the cutting performance of blunt or sharp chains. Both the cross-cutting efficiency and energy consumption are six times higher when using a blunt chain, whereas it has to be explained that the level of chain bluntness influences the result. In a regular working environment, the chain is normally sharpened immediately when the size and shape of sawdust changes, when smoke appears, or when additional force has to be applied in order to continue sawing [40]. In the experiment, however the level of chain's bluntness was higher than in regular working environment. A chainsaw with a blunt chain causes a higher vibration load [41].

Large differences in cross cutting efficiency and energy use in relation to the level of chain sharpness indicate that scientific approach to chain sharpness levels is required to enable comparisons between research. The method development could be based upon the radius of cutter tooth, which increases with wear [33]. Although the statistical significance of the influence of chain tension onto cutting speed has not been confirmed, the chain tension should be controlled in all scientific publications. Accordingly, we propose that the mass with which the chain is tensioned is standardized in relation to chain length and pitch. Determination of the chainsaw power is also problematic, as internal combustion engines have different power to torque characteristics than their electric counterparts

where torque is constant, which makes direct comparisons impossible. Therefore, a scale that would enable comparing both types of engines is a necessity.

In the study, we did not find evidence that overtensioning of the chain increases the time of cross cutting or energy consumption. Therefore, the development of automatic tensioning system does not seem reasonable. However, when understanding that chain tension influences safety at work, and the wear of chainsaw, the integration of an automatic tensioning system becomes viable [27,33]. When choosing the type of electric saw to purchase, it is better to choose a saw with high efficiency, regardless of electricity consumption, as the share of the energy cost is low in comparison to price of work. For efficient work, regular maintenance of the saw and all its components is a requirement.

5. Conclusions

The advantages of using electric chainsaws are related to the aspects of emissions, portability, lower acoustic pollution, and lower vibration levels caused by the electric motor, while the disadvantages remain in the need for access to an electrical grid, the need for regular maintenance of sawing parts, and efficiency, where differences between different models occur.

Our data were obtained from a partial factorial experiment, in which three electrical cordless chainsaws were compared in terms of cutting performance by determining cross-cutting time and energy consumption, while controlling the influence of chain sharpness and tension adjustment. The results show that the chain tension has no significant influence on the time of cross cutting or electricity consumption. However, the electricity consumption and cross cutting time were significantly different when comparing the saws used in the experiment. The energy consumption and the time of cross cutting were significantly higher when blunt chains were used, with a large difference between the time of cross cutting and the electricity consumption.

The study highlighted the fact that, despite all the differences between the saws when using electric and conventional chainsaws, the maintenance of the cutting parts is crucial to ensure productive work and low energy consumption. An important message is that the speed of cross cutting and low energy consumption is determined by choosing the right type of saw and ensuring the correct chain sharpness, not by improving chain tension.

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