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Influence of Chain Filing, Tree Species and Chain Type on Cross Cutting Efficiency and Health Risk

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Abstract: As one of the major parts of the chainsaw, the cutting chain has an important impact on productivity and health risk in motor-manual harvesting. The efficiency of cross cutting and quantity of sawdust produced in relation to different cutting chain settings, chain producers and wood species has been measured. The trial was set up to include two tree species (fir and beech) and saw chains from two different producers. The chains were filed at three different top plate filing angles and depth height gauges. All factors were significant in terms of cutting efficiency and wood dust production. The top plate angle recommended by producers proved to be the most efficient, with the smallest quantity of inhalable wood dust. Cutting chain settings can be adapted to the specific requirements of the user; however, safe working practices should be followed. Significant differences between chain producers mean that users should conduct rational decision making when choosing a saw chain.

Keywords: forestry; chainsaw; filing; sawdust; safety

1. Introduction

The introduction of mechanized harvesting has been hindered by several factors, including steep terrain, ownership fragmentation and close-to-nature management [1]. Motor-manual tree felling and processing using a chainsaw therefore remains the predominant harvesting method in many regions of the world (South East Europe, Asia, Africa) [2–4]. Additionally, the low investment cost and the chainsaw's versatility play a significant role when harvesting technology is chosen in private forests [5–7]. The chainsaw's simplicity and inherent reliability make it ideally suited for the harsh working conditions commonly encountered in forest operations.

Petrol chainsaws have recently witnessed a steady, but slow increase in cutting efficiency related to increases in engine power and speed, and improvements in the control of engine performance. Higher efficiency reduces the amount of time and energy required for the production of one unit of goods. Therefore, increased productivity reduces greenhouse gas emissions, which are considered to be the main cause of climate change [8].

Unfortunately, motor-manual forest work is inherently dangerous [9,10], physically demanding [11,12] and involves physical environmental factors which have an extremely detrimental effect on worker health. Workers engaged in motor-manual cutting are exposed to excessive noise and vibration [13–15] and to the effects of exhaust gases [16], floating particles of mineral oil and airborne wood dust [17–19].

Although the air in logging operations can be very polluted [20], very few motor-manual workers are aware of the negative consequences of exposure to dust. The risk, however, is significant, and the International Agency for Research on Cancer has classified hardwood dust as a human carcinogen [21]. It is estimated that in 25 member states of the European Union, 2% of the work force is occupationally exposed to inhalable wood dust [22]. In the European Union the Directive 99/38/EC [18], is setting the legal limit for the exposure to inhalable wood dust at 5 mg/m^3, as an average of an 8-h working day. In regard to the size of particles inhalable, thoracic and respirable particles are to be distinguished [23]. In our study however, as a health risk indicator, the share of the inhalable wood dust in regard to the total amount of saw dust was used [24].

Potential health effects from exposure to wood dust are numerous and well documented [25] and include changes in pulmonary function and allergic respiratory response (asthma). The most serious problem arising from exposure to wood dust is the risk of developing cancer, particularly nose and sinus adenocarcinoma [26].

The saw chain, as the main sawing part, influences the efficiency, safety and ergonomic suitability of the chainsaw. The main problem for the user is that only the technical data that are needed for compliance of the chain with the saw bar are available for any single chain. There is no, or insufficient, qualitative data needed for rational decision making. Producer information about quality, i.e., "chain with lower vibration," is more a function of faith in a trademark than of rational thinking. The problem is exacerbated because of the lack of knowledge available about basic principles of how efficiency or health risk change depending on chain maintenance practices.

Practice and science agree that proper filing and maintenance of the saw chain is crucial for safe and efficient work [27]. The word "proper" usually means that users have followed the producer's directions. In practice, however, modification of filing direction and depth is common, with implications for chain durability and work efficiency.

Since the cutting chain is one of the most important parts of the chainsaw, its preparation and maintenance have a direct impact on work efficiency and health risk. The aim of the study was therefore to determine the factors affecting efficiency and the amount of inhalable wood dust produced during cross cutting with a chain saw. To achieve these goals, the experiment has been set up including two filing factors, two tree species and two saw chains from different producers. The effect of wood moisture was controlled, as it has been established that it affects particle size distribution [28].

According to our experience and previous studies, it was expected that the chain setting recommended by the producer would yield the greatest efficiency and the lowest health impact, as the indicated values are presumably the result of in-depth analysis performed by the chain producer. The chains were chosen from two established producers, and tree species were chosen according to their predominance in Central Europe, although no specific hypotheses were proposed based on these factors.

2. Materials and Methods

The experiment was designed as a full factorial design (Table 1) with two factors at two levels and two factors at three levels ($2^2 3^2$). To eliminate the possible effect of wood structure and moisture, each combination was repeated five times (Scheme 1). The positive effect of repetition of cross cutting on experimental design was confirmed with an insignificant difference in wood moisture between all factors involved in the experiment with the exception of tree species. The average wood moisture was 32.9% for fir (*Abies alba* Mill.) and 50.6% for beech (*Fagus sylvatica* L.). The total number of crosscuts with repetitions was 180 or 10 by each saw chain setup. For the purpose of wood dust analyses, additional crosscuts (11th and 12th crosscut, Scheme 1) were done at all factorial levels but without repetitions (n = 36).

Table 1. Description of factors, their respective levels, coding and specification of variables for saw chain comparison test.

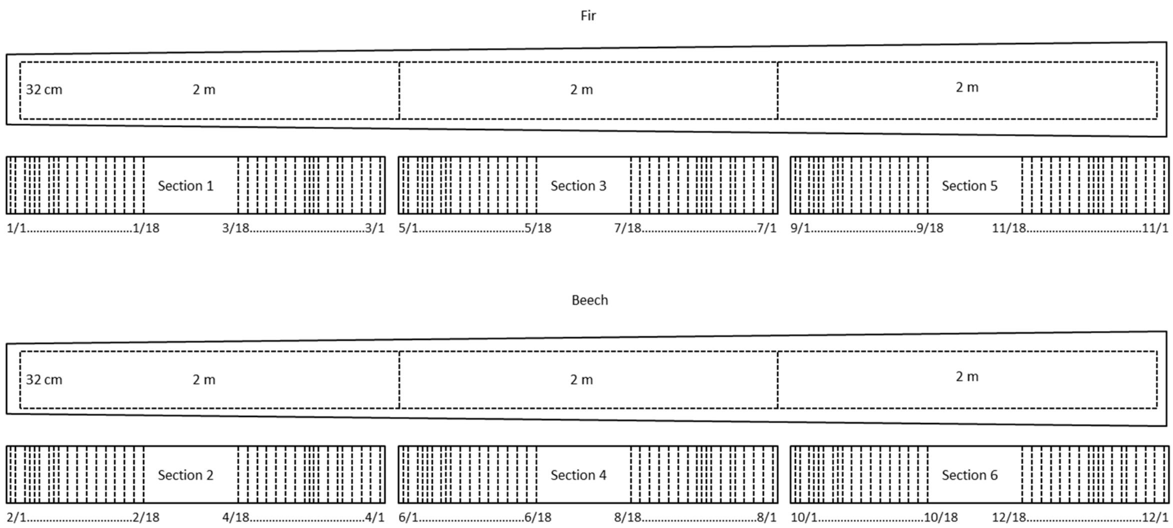
Factors	Variable Description	Levels	Coding	Unit	N [1]	Mean	Standard Deviation
Cross cutting time	Continuous variable indicating duration of cross cutting.	-	*t*	s	180/0	26.39	10.44
Sawdust structure	Continuous variable indicating weight structure of chips distributed in three classes.	>3 mm	*wtB*	%	0/36	52.87	10.34
		0.125 mm <>3 mm	*wtM*	%	0/36	45.66	10.14
		<0.125 mm	*wtS*	%	0/36	1.49	0.87

Table 1. *Cont.*

Factors	Variable Description	Levels	Coding	Unit	N [1]	Mean	Standard Deviation
Top plate filing angle	Dummy variable indicating angle of the cutting tooth. The filing angle was between 15–40°, depending on the type of chain and producer. The producer proposed filing angle is marked as 0°.	−10°	*A − 10°*	-	60/12	-	-
		0°	*A0°*	-	60/12	-	-
		+10°	*A + 10°*	-	60/12	-	-
Depth gauge height	Dummy variable indicating height difference between the depth gauge and the tip of the tooth cutting tooth. The height difference was 0.45, 0.65 and 0.85 mm. The proposed producer's difference is 0.65 mm.	0.45 mm	*G0.45*	-	60/12	-	-
		0.65 mm	*G0.65*	-	60/12	-	-
		0.85 mm	*G0.85*	-	60/12	-	-
Tree species	Dummy variable indicating two tree species (beech and fir) indicative of Central European conditions.	Beech	*SB*	-	90/18	-	-
		Fir	*SF*	-	90/18	-	-
Chain producer	Dummy variable indicating two producers of saw chains.	Producer 1	*P1*	-	90/18	-	-
		Producer 2	*P2*	-	90/18	-	-

[1] Sample size: cutting efficiency analyses/wood dust analyses.

In the trial, air dried, two first class logs of fir and beech were used. The logs were standardized into a beam with length of 6 meters and sides of 32 × 32 cm, in compliance with ISO standards [29]. The beams were cut into 6 shorter (about 2 m long) sections just before the trial (Scheme 1).



Scheme 1. Preparation and division of wood beams from two trees species into sections and cross cutting sequence. Note: 1/1-cross-cut/chain setup sequence.

A new Husqvarna 372 XP professional chain saw with a 45-cm-long Stihl Rollomatic E cutting bar was used in the experiment, and a skilled worker was employed as the chain saw operator. Eighteen 3/8″ chisel chains with 72 drive links from two different producers were used and filed in accordance with the trial scheme (Table 1). The top filing angles recommended by the chain producers differ for 5°. The top plate filing angle was done using a Stihl USG filing tool, while correct depth gauge height was achieved using hand filing and controlled with calipers.

Cross cutting took place in turns according to tree species and always in the same sequence (Scheme 1). The sequence of used chain setups was randomly selected. To further guarantee comparable conditions, cutting chain tension was controlled and the weight of the saw was kept at the same level by assuring the same level of lubricant and gasoline in the saw. The saw was controlled only through the rear handle, assuring that the pressure applied to all sample logs was constant. Visible defects in the wood were avoided when cross cutting.

The whole trial was recorded using a camera (Sony HDR-XR200; Sony, Tokyo, Japan), while the time studies were performed in the office to ensure the highest precision of measurement. A total amount of saw dust was directly captured in a plastic bag using an adapter attached to the chain saw. Moisture content was determined with the gravimetric method, according to European standards [30]. Fresh sample weight was determined immediately after sample collection with a portable scale to avoid the bias caused by moisture loss during storage and transport to the laboratory. Particle size distribution was determined with the oscillating screen method according to European standards [31]. Entire samples were sieved, and from the mass of fractions the shares of particle size distributions were calculated. The share of fine particles from the particle size distribution analysis was used as an indicator value.

Parametric multivariate analysis of variance (MANOVA), univariate analysis of variance (ANOVA) and ordinary least squares regression were used for statistical data processing. Before analysis, dependent variables were checked for normality (Kolmogorov–Smirnov and Shapiro–Wilks tests) and homogeneity of variance (Levene's test). In case of violation of data considerations, variables were transformed.

For the analysis of cross cutting duration, all samples were used (n = 180). To meet considerations for use of parametric tests (MANOVA, ANOVA), the dependent variable (time) was transformed with the inverse square root transformation.

Because of the interdependent nature of particle size distributions, basic approaches of compositional data analysis were used [28]. Compositional data were transformed using Isometric Log Ratio transformation in the CoDaPac software (2.02.04, 2017, University of Girona, Girona, Spain) [32]. The data were analyzed with IBM SPSS Statistics software (21.0, 2012, IBM, Armonk, NY, USA).

3. Results

3.1. Factors Influencing Cross Cutting Time

Statistical analysis of cross cutting time shows that cross cutting time is significantly dependent on all four factors: top plate filing angle, depth gauge height, tree species and cutting chain producer (Table 2).

Table 2. ANOVA results between cross cutting time (square root transformed) and independent factors.

Source	SS [1]	df [2]	MS [3]	F value	*p*-level
Corrected Model	0.100	6	0.017	29.646	0.000
Intercept	7.483	1	7.483	13,339.983	0.000
Depth gauge height	0.016	2	0.008	14.108	0.000
Chain producer	0.004	1	0.004	7.380	0.007
Tree species	0.046	1	0.046	81.318	0.000
Top plate filing angle	0.034	2	0.017	30.480	0.000
Error	0.097	173	0.001		
Total	7.679	180			
Corrected Total	0.197	179			

[1] Type III sum of squares, [2] Degrees of freedom, [3] Mean square.

In a four-factorial model (Equation (1)) with a constant level of other factors, the cross cutting time with the smallest gauge depth height is significantly shorter than the cross cutting time at the largest gauge depth height, while shorter ($p = 0.10$) than with the factory-recommended gauge depth. When comparing the top plate filing angle, the cross cutting time is the shortest when compared with the other two settings. It takes significantly longer to cut through beech logs than fir logs. Cross cutting time is significantly longer when using the saw chain of producer 2.

$$t(\mathrm{s}) = \frac{1}{(0.206 - 0.023^{***} \times G0.45 - 0.007^{o} \times G0.65 + 0.010^{**} \times P1 - 0.032^{***} \times SB + 0.023^{***} \times A - 10^{\circ} + 0.033^{***} \times A0^{\circ})^{2}} \quad (1)$$

Note: * *p*-level of significance of the effect—$^{\circ}$ $\leq$0.1, * $\leq$0.05, ** $\leq$0.01, *** $\leq$0.001; variables defined in Table 1.

With simultaneous changing of all factors in the model it can be determined which factor combinations yield the longest and the shortest cross cutting time (Figure 1). Cross cutting time reaches a maximum when the filing angle is the largest and the depth gauge height is the smallest, when using the saw chain of producer 2 and when cutting beech wood. The minimum cross cutting time is achieved using the factory setting filing angle and maximal depth gauge height when using the saw chain of producer 2 and when cutting fir wood. The maximum time (43.29 s) is 2.7 times longer than the minimum time (16.15 s).

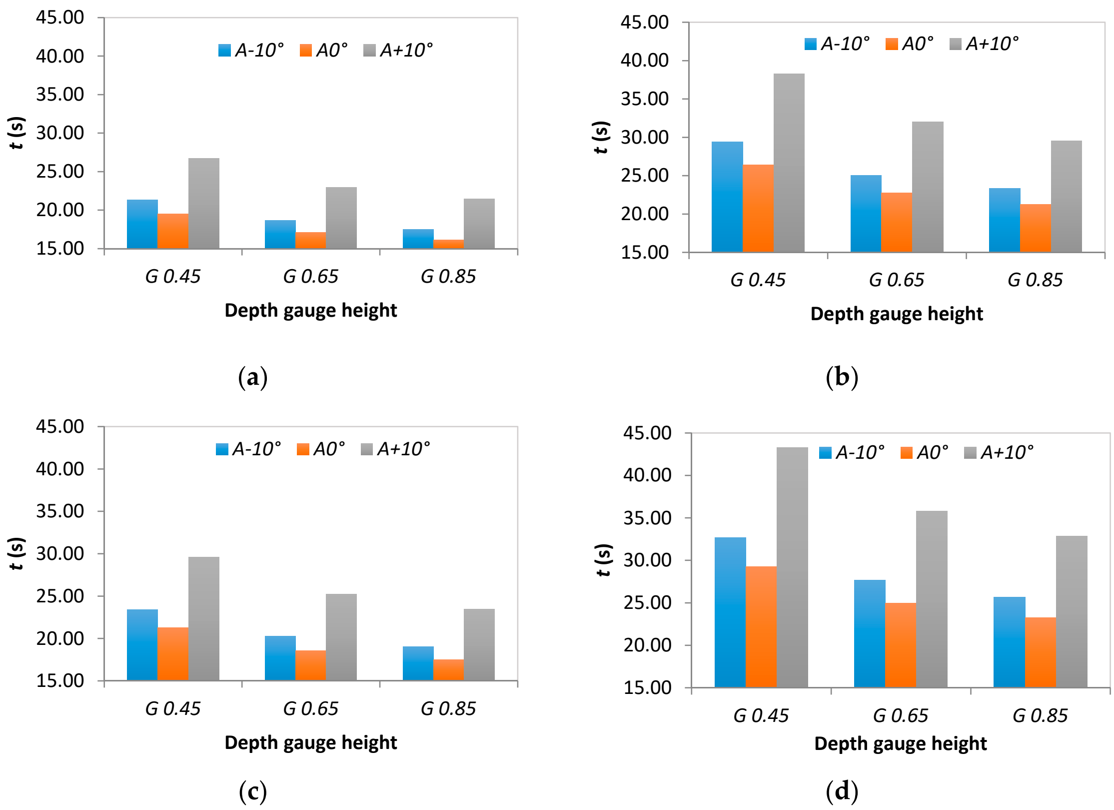


Figure 1. Dependency of cross cutting time (t) on depth gauge height (G) and top plate filing angle (A): (**a**) chain producer 1 and fir wood (minimum cross cutting time); (**b**) chain producer 1 and beech wood; (**c**) chain producer 2 and fir wood and (**d**) chain producer 2 and beech wood (maximum cross cutting time).

3.2. Factors Influencing Sawdust Structure

Using multivariate data analysis (Table 3), it has been determined that three factors, i.e., top plate filing angle, tree species and chain producer, influence the particle size distribution of sawdust.

Table 3. MANOVA results between particle size distribution and independent factors.

Effect		Value	F Value	Hypothesis df [1]	Error df [1]	p-Level
Intercept	Pillai's Trace	0.997	5476.936	2	28	0.000
Top plate filing angle		0.613	6.404	4	58	0.000
Depth gauge height		0.170	1.345	4	58	0.264
Chain producer		0.323	6.668	2	28	0.004
Tree species		0.912	145.325	2	28	0.000

[1] Degrees of freedom.

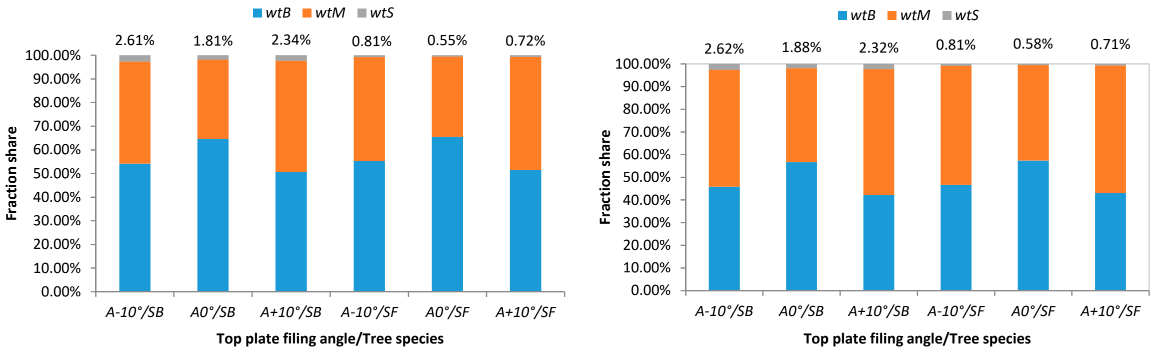
Additional univariate analysis (Table 4) shows that the relationship between the largest and middle-sized fractions of particle size distributions (ILR1) is influenced by the top plate filing angle and producer, while the relationship between the largest and middle fraction versus the smallest fractions (ILR2) is influenced by the top plate filing angle and tree species.

Table 4. ANOVA results between particle size distribution (ILR1, ILR2) and independent factors.

Source		SS [1]	df [2]	MS [3]	F Value	p-Level
Corrected Model	ILR1	1.739	6	0.290	5.551	0.001
	ILR2	9.200	6	1.533	52.511	0.000
Intercept	ILR1	0.386	1	0.386	7.398	0.011
	ILR2	322.640	1	322.640	11,049.729	0.000
Top plate filing angle	ILR1	1.092	2	0.546	10.456	0.000
	ILR2	0.450	2	0.225	7.699	0.002
Depth gauge height	ILR1	0.108	2	0.054	1.035	0.368
	ILR2	0.140	2	0.070	2.399	0.109
Chain producer	ILR1	0.529	1	0.529	10.129	0.003
	ILR2	0.049	1	0.049	1.669	0.207
Tree species	ILR1	0.010	1	0.010	0.198	0.660
	ILR2	8.561	1	8.561	293.204	0.000
Error	ILR1	1.514	29	0.052		
	ILR2	0.847	29	0.029		
Total	ILR1	3.640	36			
	ILR2	332.687	36			
Corrected Total	ILR1	3.254	35			
	ILR2	10.046	35			

[1] Type III sum of squares, [2] Degrees of freedom, [3] Mean square.

Further analysis shows that the percentage of the largest fraction is maximal when the producer-recommended top plate filing angle is used, and that it is larger when using the saw chain of producer 1 (Figure 2). The percentage of inhalable dust is lowest when using the chain of producer 1, with the filing angle recommended by the producer and when cutting fir wood (0.55%). The largest proportion of inhalable fraction (2.62%) was formed when the filing angle was the lowest, when cross cutting beech wood and using the saw chain of producer 2. The largest percentage of inhalable fraction is therefore 4.7 times higher than the sample with the lowest dust content.



(**a**) (**b**)

Figure 2. Dependency of sawdust weight structure on top plate filing angle (*A*) and tree species (*S*): (**a**) chain producer 1 and (**b**) chain producer 2. Note: *wtB*—big particles (more than 3 mm), *wtM*—medium-sized particles (3–0.125 mm) and *wtS*—small (inhalable) particles (less than 0.125 mm).

4. Discussion

The results show that the work efficiency and health risk due to inhalable dust is influenced by all of the researched factors: chain filing, tree species and chain producer. Ignorance of the above factors can result in significant differences in work efficiency and increased health risk.

From the viewpoint of efficiency and dust particles, the best top plate filing angle was the angle recommended by the chain producer. With this angle the cross cutting time and the amount of inhalable dust particles reached a minimum. These results are in direct contradiction with research that found that the top plate filing angle recommended by the producer corresponded to the greatest exposure to hand-arm vibration [33]. However, it was established that from the viewpoint of efficiency, it is better that the top plate filing angle is smaller than the angle recommended by producer rather than larger. The real-world implications of these findings are that mistakes made by less-experienced chain saw operators depend on the deviation from the recommended angle, and it is not as critical when the angle is smaller than that prescribed.

The depth gauge height has been found to deviate strongly in real-world operations, as only 15% of chains were found to have the proper gauge depths [34]. The consequence of large depth gauge height is higher cutting efficiency, while no statistically significant effect has been found on the quantity of hazardous dust particles. Excessive depth gauge heights are not recommended, as they lead to higher levels of kickback forces [35] and larger vibration loads [36]. Higher depth gauge setting increases the chain saw power requirements, and the consequences are higher fuel consumption, higher weight, higher vibration exposure and potentially greater negative impact on the health of the environment and worker. The open question remains the optimal relation between depth gauge setting and all of the above factors.

The effect of different wood species is important because of different wood density, as it was established that wood density has a significant effect on hand-arm vibration exposure [15]. The influence of the user on this factor is relatively small, as this factor depends on the worksite. However, a detailed analysis of interactions between factors has shown that the species influences cutting efficiency through the factors of top plate filing angle and saw chain producer. The dependency was confirmed by the experience of cutters, who often alter chain angles depending on whether the work is in hardwood or softwood forests. Another possible cause for differences in work efficiency and health risk is the wood moisture content, which is significant between tree species.

Few studies have examined exposure of forest operators to wood dust, but it was determined that exposure to dust was 1.5 mg/m^3 for all operations except coppicing, where loads were greater [18]. Most loads, however, were lower than the EU occupational exposure limit (OEL) of 5 mg/m^3. This level has been disputed, as some countries have lower allowed OEL levels, and the figures reported in the above study are above the allowed levels in some EU countries. In the article it has been shown that the amount of inhalable dust particles can be effectively lowered with the use of different filing angles. Also, salvage cuts of trees that have remained in the forest long enough for the wood to become dry should be avoided, as such trees are associated with a higher risk of accidents [10] and the risk of high concentrations of inhalable dust particles [37]. Additionally, the cutting chain preparation in the studies is usually not controlled, but it has been demonstrated that it is indeed a very important factor when conducting sawdust analysis, as it influences sawdust composition and therefore the amount of inhalable dust produced. The measured quantities of inhalable wood dust are to be considered as potential risk for health, since it is assumed that only part of inhalable saw dust enters the air and a part of that dust enters the worker's body.

One of the main conclusions is that producers do not produce equivalent chains. The chain type therefore influences the cutting efficiency and the health risk for the chain saw operator. Furthermore, after a number of cuts the performance and risk for health [15] may change because of different durability of chains. The results clearly demonstrate that a rational decision when purchasing a saw chain is crucial, and force producers into continued technological development.

It has to be acknowledged that in the study only two factors were taken into consideration from the pool of factors that influence the suitability of a saw chain for professional use. For instance, the viewpoint of safety at work in the sense of vibration exposure has not been included, and protection against kickback. It is assumed that the producer carefully weighs all of the above considerations when designing the product, and chooses the optimum accordingly. The results, however, show that it would be reasonable to provide not only one filing angle, but several, or to develop chains specifically intended for conifers or broadleaves.

From the lessons learned, the extension of scope in similar future studies is suggested, especially the inclusion of additional parameters, such as fuel and lubricant consumption, hand-arm vibration, different wood moisture levels, different lengths of cutters, direct measurements of airborne wood dust emissions and durability and life span of saw chain. Also, there are other, smaller chain saws, i.e., non-professional and electric chainsaws that use smaller chains and that could significantly alter the results. It has been found that the wood species also influences kickback forces [35], and an important safety consideration is how the filing angle influences the kickback of the saw in relation to wood species. Certainly, it would have the highest value for practice by testing different chains, their lifespan and their properties in real-life conditions during forest operations.

Unfortunately, the safety improvements offered by high mechanization are unattainable for motor-manual work [38,39]. It is therefore necessary to continually improve machines to make work as friendly to the worker as possible. Although all of the saw chain producers advertise safety features, and it is clear that it is necessary for producers to make complex decisions related to optimization in order to achieve these goals, more work should be done on the topic in order to provide more accessible and transparent information about saw chains.

5. Conclusions

The study demonstrated that cutting chain selection and proper chain preparation are crucial for achieving high productivity and reducing health risk. There was a more than two-fold difference in efficiency and quantity of inhalable wood dust between the best and worst cutting chain set up, making the chain one of the most important parts of the chainsaw which critically influences work with this machine. Additionally, the results proved that the chain settings recommended by the chain producers yield the greatest efficiency and the least health impact. It is evident that the recommended settings are the result of the optimization of the factors examined in the study. The results also suggest that the filing angle should change according to tree species, but safe working practices must be followed.

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