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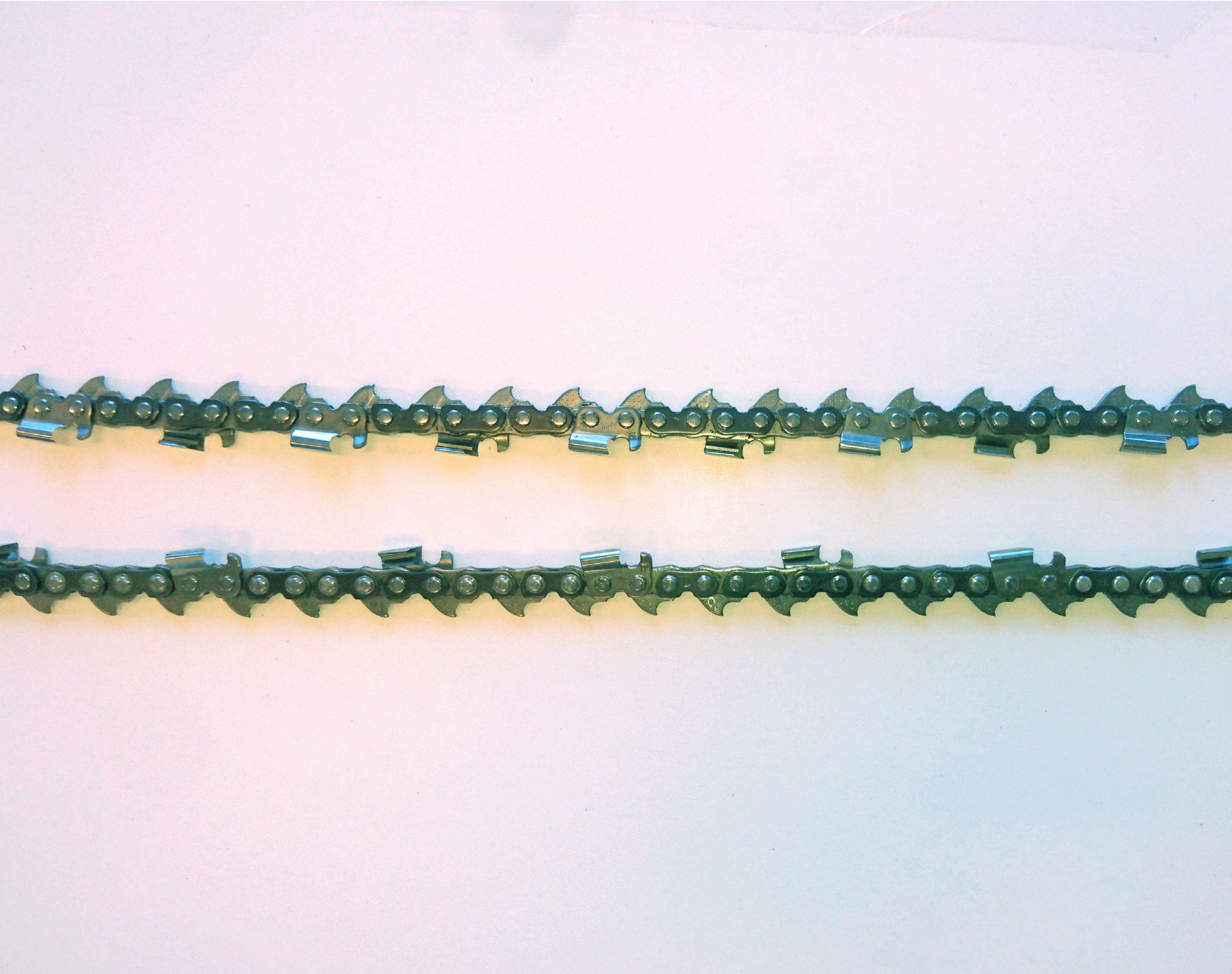
Cutting capacity of new and reground saw chains

Avverkningskapacitet för fabriksnya och slipade sågkedjor



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Foreword

This report summarises the results from the study ”*Cutting capacity of new and reground saw chains*”. The study was part of the ‘Smart Innovation’ project run by Skogstekniska Klustret (The Cluster of Forest Technology). The project was part-financed by the European Regional Development Fund, Region Västerbotten, universities, municipalities and the members of Skogstekniska Klustret. The study was also financed by Sveaskog and from the Skogforsk framework funding.

Ljusdals sliptjänst AB, AB Mora Slipservice, RM Kedjeservice AB and Slipsten AB ground the chains used in the study. Sveaskog provided the logs from which discs were cut.

The following were the contacts from the respective companies:

Mats Nyberg, Ljusdals sliptjänst AB

Rose-Marie Lindberg, Mora slipservice AB

Robert Modig, RM Kedjeservice AB

Sten Ahlström, Slipsten AB

Lena Jonsson, Skogstekniska klustret ek. för.

Linnéa Carlsson, Sveaskog Förvaltnings AB

Claes Kindblom, Sveaskog Förvaltnings AB

Thorbjörn Westman, Sveaskog Förvaltnings AB

Cutting time and energy consumption were measured on the test rig built up at the Skogforsk facility in Sävar. For the study, Komatsu Forest contributed a harvester head, a hydraulic power pack, and expertise regarding the harvester head. Parker Hannifin contributed a F11iP saw motor and expertise regarding adjustment of the motor.

Data was collected and analysed by a working group from Skogforsk, comprising Mikael Andersson, Björn Hannrup and Petrus Jönsson. Rolf Gustafsson at Himlinge Skogsservice provided valuable advice during the course of the study.

Petrus Jönsson and Björn Hannrup had overall responsibility for planning and implementing the study.

Grateful thanks to everyone who participated!

Uppsala, 2 November 2018
Petrus Jönsson, Björn Hannrup & Mikael Andersson

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Summary

One aim of the study was to compare a new chain model, the Oregon 19HX, and a saw chain with fewer cutting teeth (a 'skip' chain) in terms of cutting time, energy consumption and bar feed force. Another aim was to examine associations between certain grinding parameters, such as different angles on the cutting teeth, and performance of the saw chains. The study was limited to new/reground chains, cutting fresh, unfrozen wood of Norway spruce. All measurements took place on the test rig built up at Skogforsk in Sävar, where a F11-iP saw motor was used.

Twelve chains were used in the study. The new Oregon 19HX chain was compared with new chains of the models Carlton B8 and Stihl RMHS. The number of cutting teeth on the skip chain was reduced by a third, and the chain was compared with a standard chain of the same model with a full set of cutting teeth. Eight reground chains were tested, all of them modified versions of the Carlton B8 model. Three of these were ground according to the standard grinding of three grinding companies. The other five were modified in terms of either the filing angle, the cutting angle, depth guage setting, more aggressive grinding in the bottom part of the cutting teeth, or grinding down to a state corresponding to that of the end of the chain's life.

Measurements were carried out during cutting of discs from 12 logs with diameters between 131 and 457 mm. From most of the logs, measurements were recorded from three cuts per chain. The energy consumption during the cutting process was determined from measurements of torque and rotation speed of the outgoing axle of the saw motor. Information about the torque of the saw motor was also used to determine the cutting time, using algorithms that identified the start and stop points for the cut through the stem. The bar feed force was calculated from measurements of the hydraulic oil pressure on the bar feed cylinder's piston rod and cylinder side, the piston areas for these two sides, and the length of the lever arm between the bar feed cylinder and the bar.

The results showed that the performance of the new Oregon 19HX chain was very similar to that of the Carlton B8 chain for all cut-related parameters investigated in the study. However, compared with the Stihl RMHS, these two chain models had 6-8% longer cutting time, 9-11% higher energy consumption, and used 16-21% greater bar feed force. Expressed as cutting capacity in a cross-sectional area of 1000 cm^2 the Stihl RMHS cut 1290 cm^2/s; the corresponding figure for the Oregon 19HX was 1197 and for the Carlton B8 was 1225 cm^2/s. In a study of a new harvester equipped with the same saw motor as in our study, and a chain model corresponding to the Carlton B8, a cutting capacity of 1222 cm/2 was measured, indicating that the absolute figures for cutting capacity as measured in the test rig are also relevant for felling by a harvester.

The skip chain had 12% longer cutting time, 16% higher energy consumption, and used 49% greater bar feed force than a corresponding chain with a full set of cutting teeth. Our interpretation of the longer cutting time for the skip chain is that the smaller number of cutting teeth reduced cutting capacity more than the corresponding potential increase in the chain's ability to evacuate chips and other debris. However, the most noticeable difference was in the bar feed force, where the Skip chain used nearly 50% greater force The Skip chain has fewer teeth in action during cutting, and the high bar feed force for this chain indicates that the saw motor used (Parker F11iP) increased the bar feed force to reduce the rotation speed on the output shaft of the saw motor down to a chain speed corresponding to 40 m/s.

The differences in cutting time between the reground chains were generally small, but the results showed that the parameters with a favourable effect on cutting time were a greater filing angle in combination with a higher cutting angle, a lower depth gauge setting, and more aggressive grinding in the bottom part of the cutting teeth. The biggest effect on cutting time was obtained for the chain with greater filing and cutting angles in combination with a lower depth gauge setting.

In summary, the study indicates some potential to shorten the cutting time of current chains by modifying the grinding pattern, but that this potential is limited. If the cutting capacity of machine saw chains is to be significantly increased, current chain models need to be further developed.

Introduction

Cutting tree stems is a key task in the work of a harvester. The cutting process comprises 7-11 percent of the effective work of the harvester (T. Brunberg, pers. comm. 2015; unpublished follow-up of harvester machine data), so the cutting time has a significant effect on harvester productivity. Furthermore, there is an association between cutting time and occurrence of bucking splits (Hannrup & Jönsson, 2010). Measures that help to shorten cutting time therefore have a potentially positive effect on both harvester productivity and timber value.

One factor crucial to the harvester's cutting time is the cutting capacity of the saw chain. Few published studies have focused on the cutting capacity of different saw chains. Consequently, most of the knowledge that has accumulated on saw chains is not generally available; instead, it is integrated in companies that manufacture saw chains and cut-related equipment. To increase the amount of published data on saw chain performance, it is important to stimulate further development and provide objective information to the users of saw chains.

A recent study showed differences in cutting time and energy consumption between new chain models (Jönsson et al. 2016). Three of the chain models in that study had almost identical cutting time and energy consumption, while the fourth, the Stihl RMHS, had 6-7 percent shorter cutting time and lower energy consumption than the other three models. The probable explanation put forward in the study was that the Stihl RMHS has a greater cutting tooth area and a lower cutting angle (see definition in Appendix 1), indicated by a greater average chip size compared with the other chain models. The study was based on chains from the market-leading manufacturers, so the study shows cutting time and energy consumption for most of the new chains used in harvester felling in Sweden.

A type of chain that is currently not used in the Swedish market is the 'skip' type, which has fewer cutting teeth than the common chain models (Wikipedia 2018). The longer spacing between the cutting teeth should mean that evacuation of chips and other debris during cutting should be more efficient with this type of chain. If chip evacuation is a limiting factor, the longer spacing could increase the cutting capacity for this type of chain. However, there is no published data to support this, and studies that examine cutting time and energy consumption of Skip chains under Nordic conditions are urgently needed.

When used in harvester felling, a chain is reground an average of 2.5 times during its lifetime (Hallonborg 2003). This means that, under production conditions, reground chains are more common than new chains. The grinding pattern is therefore a crucial factor in the actual cutting capacity and the energy consumption in mechanical felling. In a study by Jönsson et al. (2016), a new Carlton B8 chain was compared with a reground chain of the same model. The cutting time for the reground chain was 9-10 percent shorter and energy consumption was less than for the corresponding new chain. The probable explanations put forward for the differences were higher filing and cutting angles for the reground chain. The study was based on only one reground chain model, and there are no published studies that examine general associations between the grinding angles on the cutting teeth and the chain's cutting capacity. One important area for future studies is to use data gathered from controlled experiments to identify these associations.

Goals and limitations

The overall objective of the project is to help reduce cutting time, thereby increasing harvester productivity and timber value. The goals of the project were:

- Based on measurements in the Skogforsk test rig, to compare cutting time and energy consumption for a skip chain with the corresponding chain model with a full set of cutting teeth.
- To evaluate a new chain model from one of the leading chain manufacturers, recently launched in the Swedish market.
- In the same study, to examine associations between the grinding angles on the cutting teeth and the chain's cutting capacity and energy consumption.

The study is limited to examining cutting time and energy consumption of new and reground chains. If the study were to show differences in cutting capacity between the chains, we intend to continue with studies examining how the different chains are affected by wear.

Materials and methods

EXPERIMENTAL DESIGN

In the study, new chains from three chain models, the Stihl RMHS, the Carlton B8 and the Oregon 19HX, were evaluated (Table 1). The latter has only recently been introduced on the Swedish market, while the Stihl RMHS and Carlton B8 have been evaluated in a previous study (Jönsson et al. 2016) but were included in this study to enable comparisons. The skip chain used in this study was a modified Stihl RMHS chain with two drive links between each tooth, which reduced the number of cutting teeth by one-third, a full-skip chain (Figure 1).

Figure 1. Photo of the full skip chain, with two-thirds of the number of cutting teeth in a standard chain.

All the reground chains were of the Carlton B8 chain model. These were ground according to the normal production grinding of the participating grinding companies, or were ground in a special way for the purposes of the study (see Table 2 for specification of the grindings). The chains were ground by AB Mora slipservice, Ljusdals sliptjänst AB, RM Kedjeservice AB and Slipsten AB. Mora slipservice used a Marcusson grinder with a ceramic grinding wheel, while other grinding companies used grinding wheels of the harder material, cubic boron nitride (CBN) fitted in ANAB grinders or ANAB machines that had been modified.

All the evaluated chains had 96 drive links and a groove width of 2.0 mm. In the study, only one chain was used per treatment, i.e. a chain was only represented by one manufacturing batch. This was because the results from an earlier study (Jönsson et al. 2016) indicated small differences within chain models between different manufacturing batches.

Table 1. Table showing the different chains used in the study.

Chain no.	Category	Manufacturer	Model	Chain type	Grinding company
1	New	Stihl	RMHS	Standard	
2	New	Stihl	RMHS	Full-skip	
3	New	Oregon	19HX	Standard	
4	New	Carlton	B8	Standard	
5	Reground	Carlton	B8	Standard	Mora sliptjänst
6	Reground	Carlton	B8	Standard	RM Kedjeservice
7	Reground	Carlton	B8	Standard	Ljusdals sliptjänst
8	Reground	Carlton	B8	Standard	Ljusdals sliptjänst
9	Reground	Carlton	B8	Standard	Ljusdals sliptjänst
10	Reground	Carlton	B8	Standard	Slipsten AB
11	Reground	Carlton	B8	Standard	Ljusdals sliptjänst
12	Reground	Carlton	B8	Standard	Slipsten AB

The study by Jönsson et al. (2016) showed that a reground chain of the Carlton B8 model had 9-10 percent shorter cutting time and lower energy consumption than the corresponding new chain. The reground chain was modified in terms of several parameters regarding the cutting teeth. Compared with the new chain, the reground chain had higher filing and cutting angles, a lower depth gauge setting, and a more aggressive grinding in the bottom part of the cutting teeth, so grinding in the cutting teeth was deeper (Jönsson et al. 2016, Appendix 2). We were trying to isolate the effect of the different parameters that were changed in the reground chain, in order to evaluate their respective contributions to a shortened cutting time.

Table 2 shows the filing angle, the cutting angle, and depth gauge setting for the new chains (Chains 1-4) and the reground chains (Chains 5-12). The photos of the chains were taken with a stereo microscope of the Leica MS5 type with a connected digital camera, a Basler Scout scA1300. Using the image analysis software ImageJ, the angles in the photos were then measured (Figure 2).

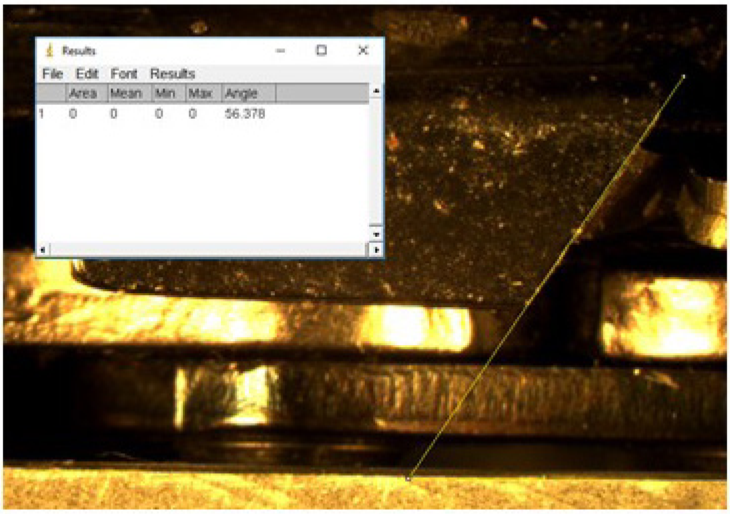

Figure 2. Photo from the stereo-microscope, taken to measure the filing angle of a cutting tooth.

The aim was to measure the angles with high precision and ensure that the standard error in the measured angles was under 1°. Definitions of the measured angles are presented in Appendix 1.

All reground chains were of the Carlton B8 model. Chains 5 and 6 were ground according to the grinding companies' standard production grinding. Chain 7 had higher filing and cutting angles and a greater depth gauge setting than the new Carlton B8 chain. Chain 7 was ground in a similar way to the reground chain used in the study by Jönsson et al. (2016), except that it was not ground as deeply in the cutting teeth (Figure 3).

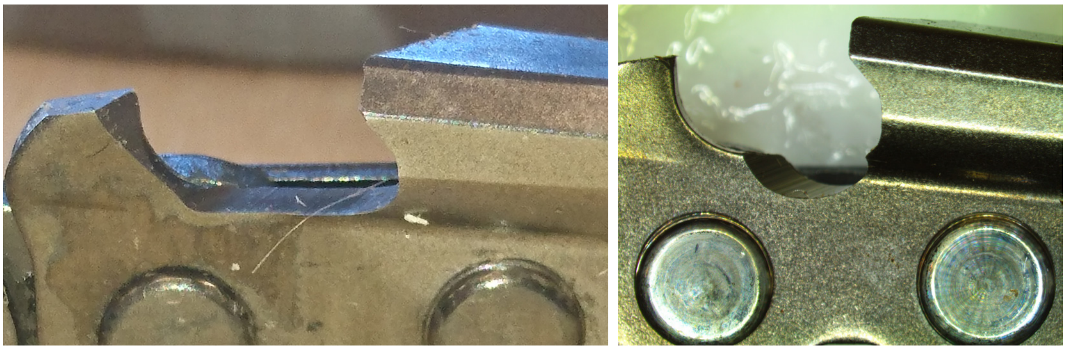

Figure 3. Left: Chain 7: the reground Carlton B8 chain with greater filing angle, cutting angle and depth gauge setting compared with the new chain. Right: The corresponding chain in the study by Jönsson et al. (2016), with the difference that the grinding extended further down in the link so the grinding was more aggressive at the bottom of the teeth.

For Chains 8-11, the aim of the grinding was to only change one variable in the cutting teeth (filing angle, cutting angle, grinding depth in the bottom part of the cutting teeth, and depth gauge setting) compared with the new Carlton B8 chain (Chain 4), thereby isolating the effects of these parameters. For Chains 9-11, this procedure was successful, apart from a minor undesirable change in the depth gauge setting for Chains 9 and 11. For Chains 8 and 12, the aim was to only change the filing angle and the length of the cutting teeth, but for these chains the grinding also led to a moderate change in the cutting angle for Chain 8 and a significant change in the cutting angle and the depth gauge setting for (Chain 12) compared with the new chain.

Table 2. Filing angle, cutting angle and depth gauge setting for the new and reground chains in the study.

Chain no.	Chain model	Filling angle (°)	Cutting angle (°)	Depth gauge setting (mm)	Changed grinding variable
1	Stihl RMHS	35	37	1,05	–
2	Stihl RMHS Full-skip	34	38	1,05	–
3	Oregon 19HX	32	37	1,0	–
4	Carlton B8	32	36	0,9	–
5	Carlton B8	32	36	1,25	Standard grinding
6	Carlton B8	37	48	1,15	Standard grinding
7	Carlton B8	45	43	1,65	Filing and cutting angle and depth gauge setting
8	Carlton B8	43	45	0,83	Filing angle
9	Carlton B8	33	45	0,78	Cutting angle
10	Carlton B8	32	36	1,58	Depth gauge setting
11	Carlton B8	32	36	1,05	Deeper grinding of cutting teeth
12	Carlton B8	37	52	1,46	Cutting teeth ground

The three chain models that were compared with new chains had similar filing and cutting angles on the cutting teeth (Table 2). However, there was some variation, where the Stihl RMHS had a somewhat higher filing angle and a lower depth gauge setting than the other two chain models.

For the Oregon 19HX and Carlton B8 models, the cutting teeth were of the chamfer chisel type, while the cutting teeth on the Stihl RMHS were of the semi-chisel type (Figure 4, Table 3). The semi-chisel type has a more rounded shape, while the chamfer chisel type has a bevelled corner.

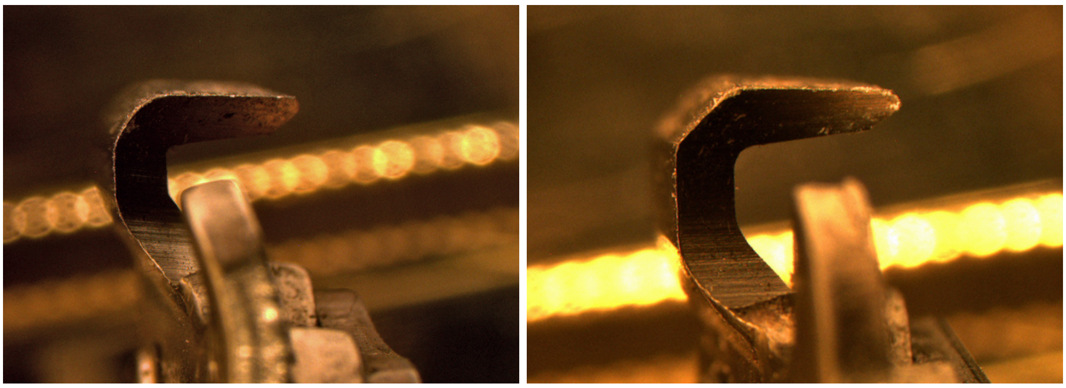

Figure 4. Front-view photo of the two types of cutting tooth in the chain models in the study.
Left: semi-chisel. Right: chamfer chisel.

The cutting teeth on the new Oregon 19HX chain had very similar measurements to those on the Carlton B8 chain. However, the Oregon 19HX was 3 percent heavier. When these two chain models were compared with the Stihl RMHS, differences were found, mainly in terms of cutting teeth length, where the cutting teeth on the Stihl RMHS were longer. In total, this resulted in the Stihl RMHS having a cutting tooth area (seen from above) that was approximately 20 percent greater than for the other two chain models (Table 3).

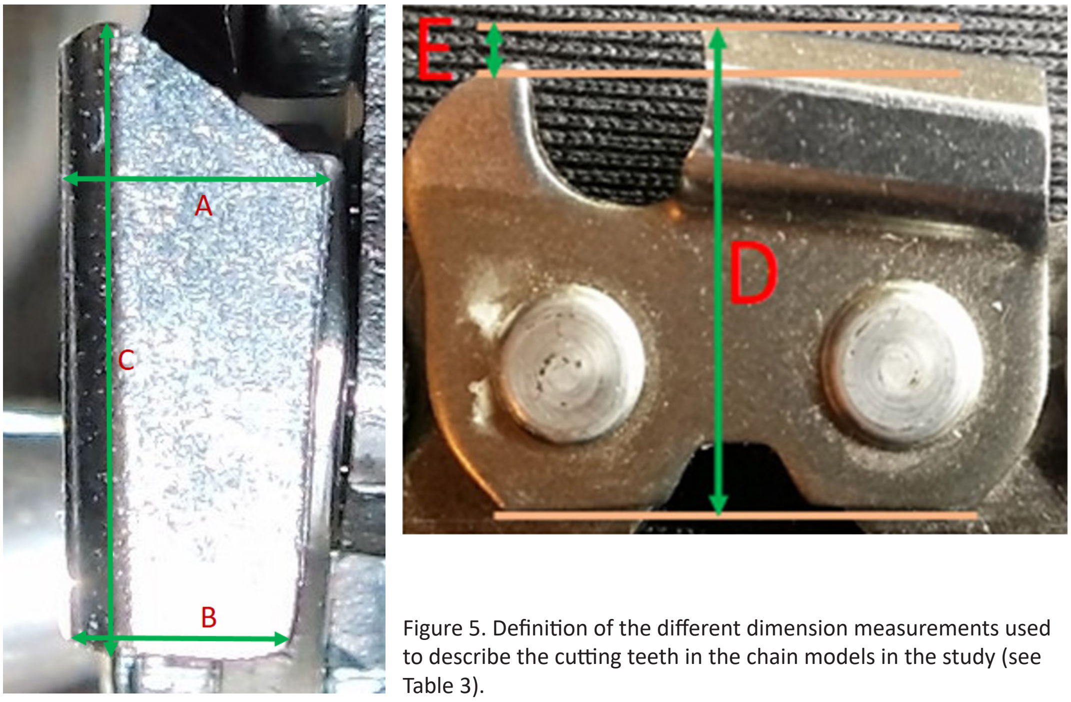

Figure 5. Definition of the different dimension measurements used to describe the cutting teeth in the chain models in the study (see Table 3).

Table 3. Type of cutting tooth, dimensions of the cutting teeth, and the total weight of the chain models evaluated. Dimensions of the cutting teeth are defined in Figure 5.

Chain model	Type of cutting tooth[1)]	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	Weight (g)
Stihl RMHS	s.c.	5,6	4,9	12,5	15,0	1,1	825
Oregon 19HX	c.c.	5,4	4,9	10,6	14,7	1,0	813
Carlton B8	c,c.	5,4	4,9	10,8	15,0	0,9	787

1) c.c. = chamfer chisel, s.c. = semi-chisel.

MATERIALS

All measurements were taken by cutting discs from the logs in the Skogforsk test rig in Sävar (see the section 'Main components of the test rig'). The discs were cut from 12 spruce logs with diameters in the interval 131 to 457 millimeter. The logs represented a sufficiently broad diameter interval that the general associations between cutting time and cut area, and between energy consumption and cut area, could be determined for each chain. For butt logs, the first half-metre at the butt end was removed before the study, because this part of the stem often had high ovality.

From each log, measurements were taken from three cuts per chain. The only exception was one log where only two cuts per chain were recorded. This resulted in a total of 420 cuts and 35 cuts per chain over the diameter interval studied. A specific cutting order was used, where the internal cutting order between chains for cuts in logs with odd numbers was chosen by drawing lots (Figure 6). For cutting in logs with even numbers, the reverse cutting order was used.

Figure 6. The saw chains in the study were suspended in an order determined by lot for cutting logs with an odd number. The chains were marked with a chain number (see Table 1).

Logs were collected, frozen at the time, from a nearby harvest site. The logs were thawed by placing them in a greenhouse for six weeks. The temperature in the greenhouse was approximately 5°C and the relative humidity high. Based on these conditions, we assumed that, at the time of the study, the logs could be regarded as fresh and the effect of drying was negligible.

MAIN COMPONENTS OF THE TEST RIG

The discs were cut in the Skogforsk test rig in Sävar. The test rig was build around a Komatsu 360.2 harvester head from Komatsu Forest, suspended in a steel frame (Figure 7). The frame has steel walls and the safety class is Lexanrutor™ to ensure a high level of safety while enabling filming and visual monitoring of the cutting process.

Figure 7. Harvester head suspended in a steel frame.

The main components in the associated hydraulic power unit were:

- A Sisu diesel motor placed in a separate area (Figure 8).
- Two variable load-sensing axial piston pumps (Brueninghaus Hydromatik, now Bosch Rexroth) with a displacement of 145 and 130 cm^3/rotation. During the study, the smaller of the pumps was used to run the power unit.
- A mainly hydraulic pipe between the hydraulic power unit and the harvester head. The pipe length corresponds to the length of the hydraulic pipes in a conventional harvester.

The axial piston pump releases a specific flow based on a certain control signal. This was achieved by regulating the angle on the svivel plate, which controls the stroke length of the pistons. The loadsensing function (Figure 9) couples the piston stroke position with the actual pressure in the system, and thereby reduces the flow if the pressure is unnecessarily high, and increases the flow when the pressure is too low on the basis of what the load in question requires.

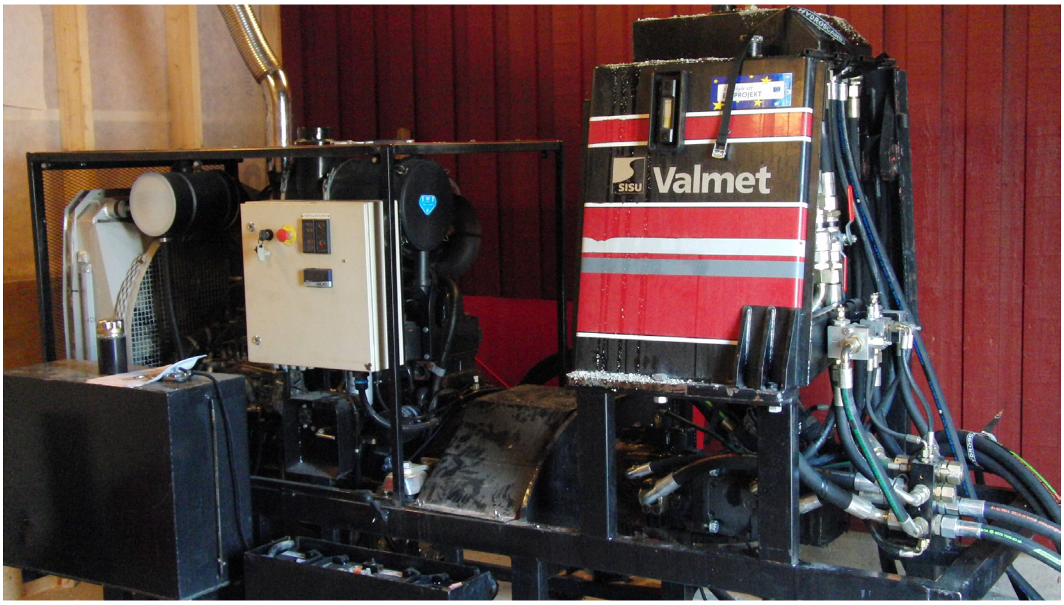

Figure 8. The diesel motor for the test rig (left) and the hydraulic power unit with tank (right).

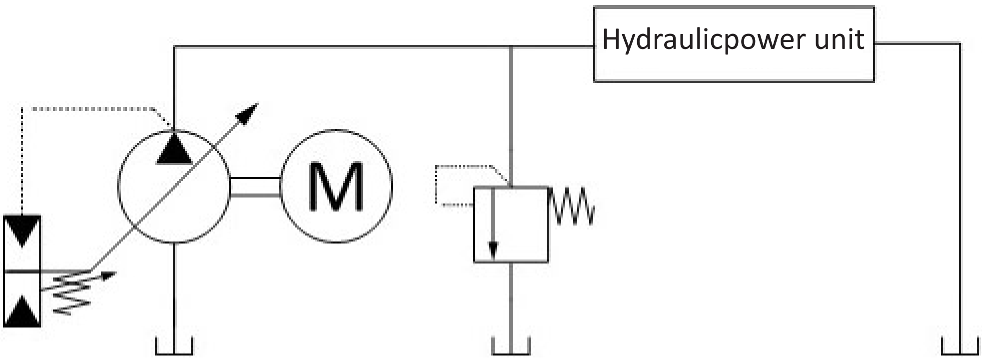

Figure 9. Simplified schematic illustration of the load-sensing hydraulic system used in the study.

The hydraulic power unit and harvester head were controlled with the Bodas RC-28-14/30 control unit from Bosch Rexroth. The software used was specifically designed in the program Bodas Design. A PC was used to communicate with the control unit via an interface (PLC). The control unit adjusts the valves to attain the desired movement. The sensors read the system, send data to the control unit, from which control currents and sensor data are sent on to the PC for logging (Figure 10). In logging of data to the PC, a sample time for the control unit of 5 milliseconds was used.

The saw unit on the harvester head was built around the F11iP saw motor from Parker Hannifin. The F11iP has an integrated hydraulic control unit that enables the chain speed to be kept constant during the cutting process. This is achieved by using a constant-flow valve that stops the flow after the motor, resulting in an even flow and thereby an even rotation speed.

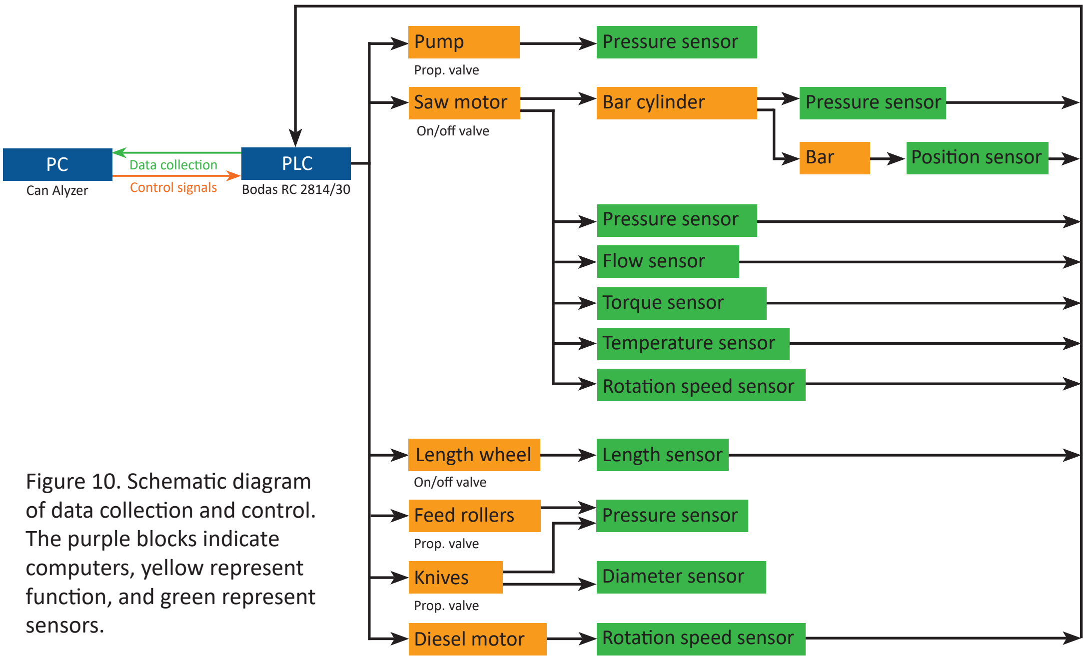

Figure 10. Schematic diagram of data collection and control. The purple blocks indicate computers, yellow represent function, and green represent sensors.

MEASUREMENTS DURING THE CUTTING PROCESS

The time taken for the cut through the stem was determined from sensor information about the saw motor torque during the cut. This indirect method for determining the cutting time has proved to correspond very well with cutting time determined through filming with a high-speed camera (Jönsson et al. 2016).

The torque was measured with an HBM torque sensor (model T22), which was attached to the output shaft of the saw motor. To make space for this sensor between the saw motor and the saw box, the saw box was modified and the output shaft of the saw motor was extended (shown by a red rectangle in Figure 11).

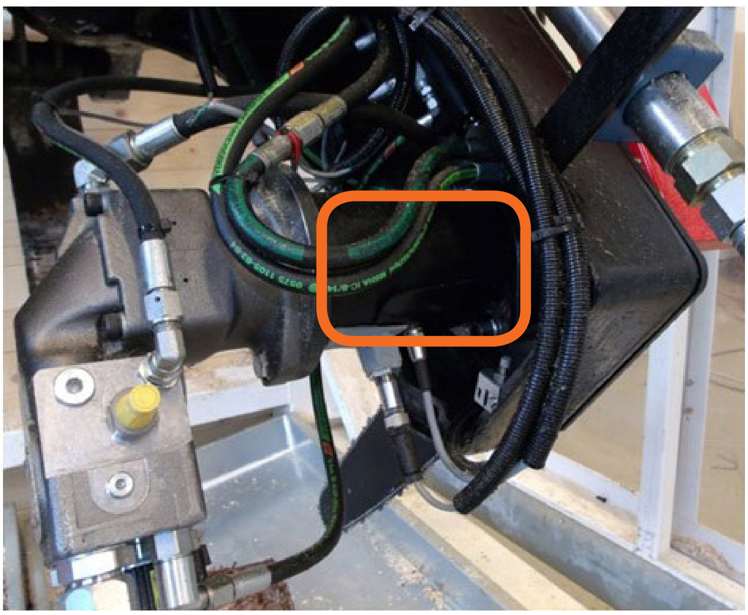

Figure 11. Photo showing how the saw motor's output shaft was extended. In the lower part of the extension (marked with a red rectangle), the torque sensor can be seen (right) and the rotation sensor left).

The saw motor rotation speed was measured with an optical sensor pointing towards the extended part of the saw motor's output shaft. The rotary encoder gave three pulses per rotation.

Flow sensors (Hydac Electronic, EVS 3104) were fitted on each saw motor pump and tank side (Figure 12). Two other sensors were fitted on the flow sensors: a temperature sensor (Hydac Electronics, ETS 4144) and a pressure sensor (Hydac Electronics, HDA 4845).

The pressure in the bar cylinder was measured with pressure sensors (Hydac Electronics, HDA 4845) fitted on the piston rod and cylinder side. The hydraulic pressure from these sensors was used to calculate the bar feed force during the cutting process (see Equations 6-8).

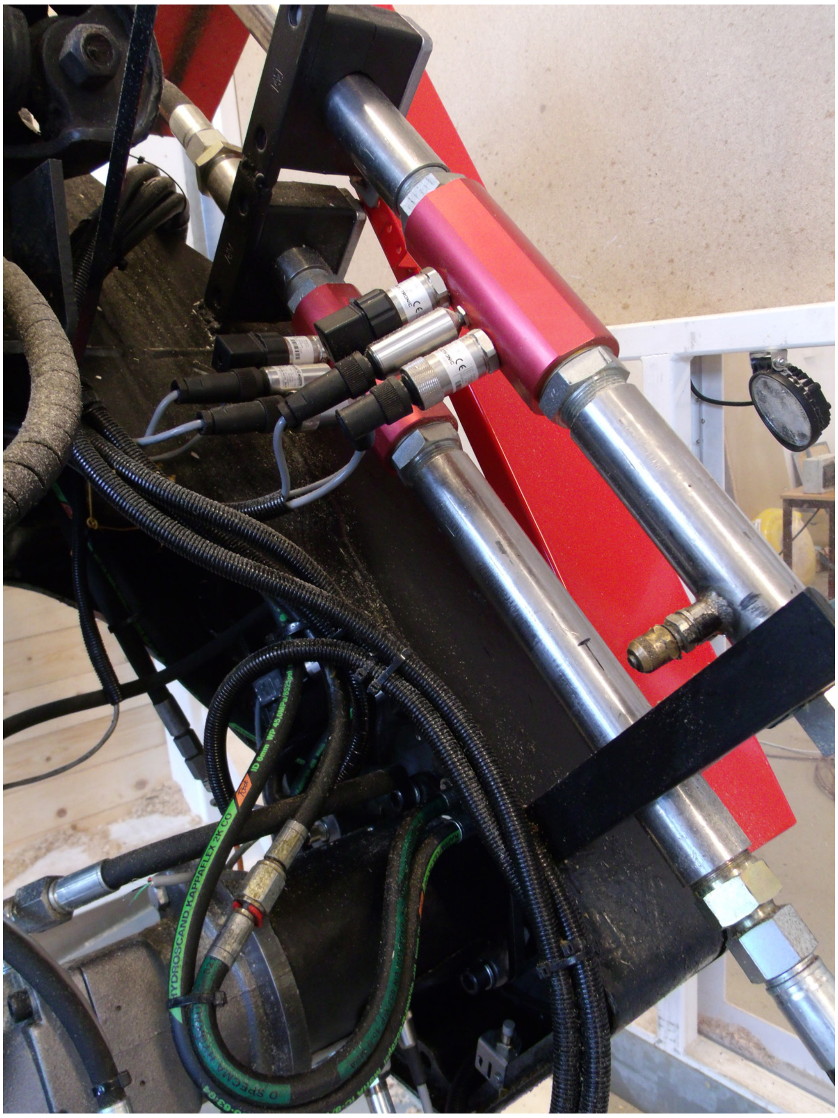

Figure 12. Sensor fitted on the pump and the tank side of the saw motor to measure the pressure, flow and temperature of the hydraulic oil.

CALCULATED VARIABLES

Cutting time was defined as the time taken for the saw to cut through the log. Previous studies indicate that calculation of cutting time on the basis of information about the saw motor torque enables the cutting time to be determined with great accuracy and precision (Hannrup et al. 2015, Jönsson et al. 2016).

The instantaneous output power of the saw motor during the cut P, expressed in (W),

is calculated as:

$$P = \tau \cdot \omega \tag{1}$$

where

τ is the torque of the saw motor's output shaft expressed in newton metres (Nm), and
ω is the rotation speed of the saw motor's output shaft expressed in radians per second (rad/s).

The total output energy E from the saw motor per cut, expressed in (J) is calculated by integrating the instantaneous output power of the saw motor over the cutting time. This is the product of the mean value between each adjacent measurement value for the instantaneous output power of the saw motor and its time difference Δt according to the equation below. This was done because the sampling time of the control unit was not constant.

$$E = \frac{1}{2}\sum_i (P_i + P_{i+1}) \cdot \Delta t_i \tag{2}$$

The mean torque μ_τ and rotation speed of the saw motor's output shaft μ_ω during cutting was obtained as a mean value by dividing the total by the total cutting time t_{kap} as follows:

$$\mu_\tau = \frac{1}{2t_{kap}}\sum_i (\tau_i + \tau_{i+1}) \cdot \Delta t_i \tag{3}$$

$$\mu_\omega = \frac{1}{2t_{kap}}\sum_i (\omega_i + \omega_{i+1}) \cdot \Delta t_i \tag{4}$$

Rotation speed for the saw motor's output shaft was converted to chain speed (v) expressed in m/s, as in the following equation:

$$v = n \cdot n_s \cdot \vartheta \tag{5}$$

where n is the rotation speed of the saw motor's output shaft expressed in rotations per minute, n_s is the number of cogs on the drive wheel (14) and ϑ is the chain split ratio, which in this case is 0.00034.

The bar feed force, F_{sm}, was calculated for the individual cuts from the force of the bar feed cylinder and the lever arm between the bar feed cyclinder and the bar. The average force of the bar feed cylinder per cut, C_k is calculated as,

$$C_k = (P_B A_B - P_A A_A) \tag{6}$$

where P indicates the average pressure during the cutting process, and A indicates the areas. The indexing A and B refer to the piston rod and cylinder side of the bar feed cylinder.

The moment τ_m that rotates around the bar holder is obtained by, in addition to the cylinder force, also considering the lever arm C_L between the bar feed cylinder and the bar. During the cutting process, the length of the lever arm changes depending on the angle of deflection of the bar. In the calculations, a fixed lever arm length of 10 cm was assumed. This length is obtained when the bar feed cylinder and the lever arm are perpendicular to each other.

$$\tau_m = C_L \cdot C_k \tag{7}$$

The bar feed force, F_{sm}, on half the bar length, L, was calculated using the following formula,

$$F_{sm} = \tau_m \cdot L \tag{8}$$

STATISTICAL ANALYSIS

Most of the cut-related parameters (such as cutting time and energy consumption) measured in the study were strongly affected by the area of the cut discs. To test whether the differences between the chains for the cut-related parameters were statistically significant, taking into account the differences in disc area, an analysis of variance was used. The area of the cut discs was then used as a covariate in the analysis (to compensate for differences in area of the discs cut by the different chains). For two of the logs, the cutting time deviated from the general association between cutting time and cut area, and for these the different chains had a different number of cuts. To compensate for this imbalance, a random effect of log was incorporated in the statistical model. The following model was adapted:

$$y = s + a + f + a(f) + e \tag{9}$$

where y is the cut-related parameter analysed, s is the random effect of log (number of log, 1-12), a is the area of the cut disc, f is the chain number, $a(f)$ is the chain number within the area, and e is the random error. The model terms f and $a(f)$ express the intercept and gradient of the regressions of the cut area for the measured cut-related parameters, by chain. In the analysis, the least square mean was calculated for each chain, i.e. the mean value for the cut-related parameters after compensation for differences in disc area.

EXCLUDED OBSERVATIONS

Twelve observations were excluded because the discs contained a large number of branches, so the cutting time was considerably increased. A further 20 observations were excluded because the signal from the torque sensor was very unclear; for these observations too, the cutting time was significantly increased. This left a total of 388 observations that could be used in the analysis.

Results and discussion

Figure 13 shows the association between cut area and cutting time for all observations. The cut area varied between 127 and 1640 cm^2, corresponding to diameters between 12.7 and 45.7 cm. The average cutting time was 0.54 s; this was reached for a cut area of just over 600 cm^2 (approximately 28 cm). There was generally a strong association between cut area and cutting time, but for two of the logs (no. 10 and 11) an increased cutting time was noted. We could find no reason for this within the framework of our study, but we have taken this into account in the statistical analysis (see 'Materials and methods').

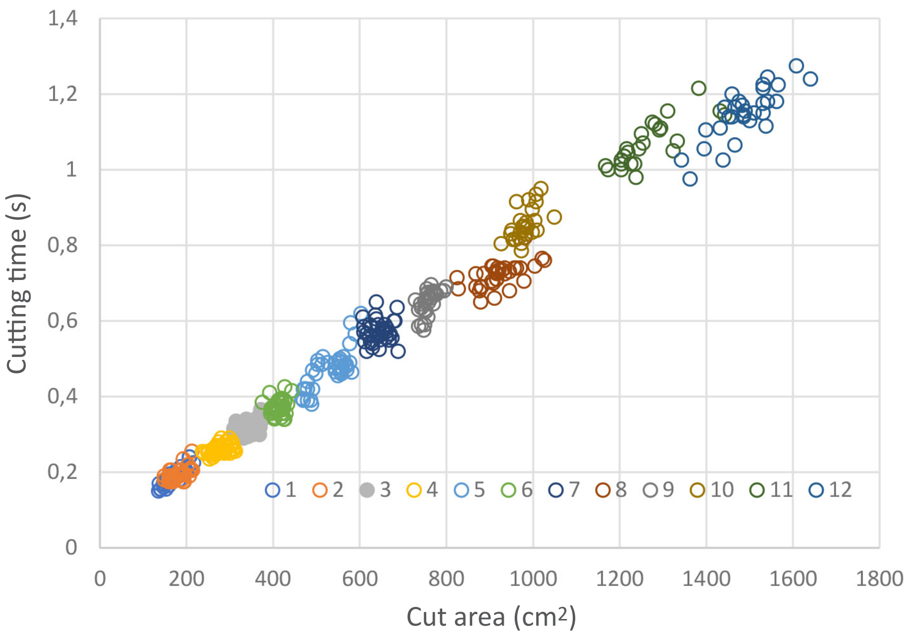

Figure 13. Association between cut area and cutting time for all observations from the 12 logs. Cuts from the different logs are shown by the different colours.

COMPARISON BETWEEN NEW CHAINS

Figure 14 shows the regression lines for cut area against cutting time for the three new chains. For two of the chains, the Carlton B8 and the recently introduced Oregon 19HX chain, the cutting times were almost identical. The Stihl RMHS chain had the shortest cutting time and, compared with the Carlton B8 chain, the difference in cutting time averaged 6.2 percent over the diameter interval studied (Figure 14). This difference was almost identical with the difference in cutting time found in a previous study of these two chains (Jönsson et al. 2016).

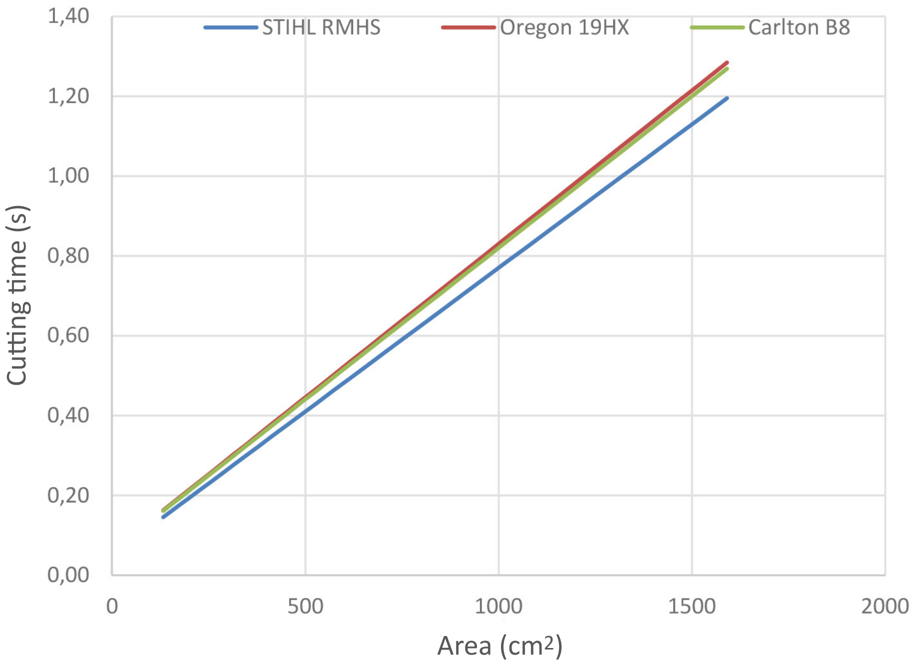

Figure 14. Regression lines for the association between cut area and cutting time, new chains.

Tests of significance of the average cutting time of the chains showed that the difference between the Stihl RMHS and the other two new chains was statisticially significant, with a high degree of significance ($p < 0.0001$), see regression equations in Appendix 2. The difference in average cutting time was caused by a lower gradient on the regression lines for the Stihl RMHS chain compared with the other two chains (Figure 15). These differences in gradient of the regression line were statistically significant with a high level of confidence ($p < 0.02$).

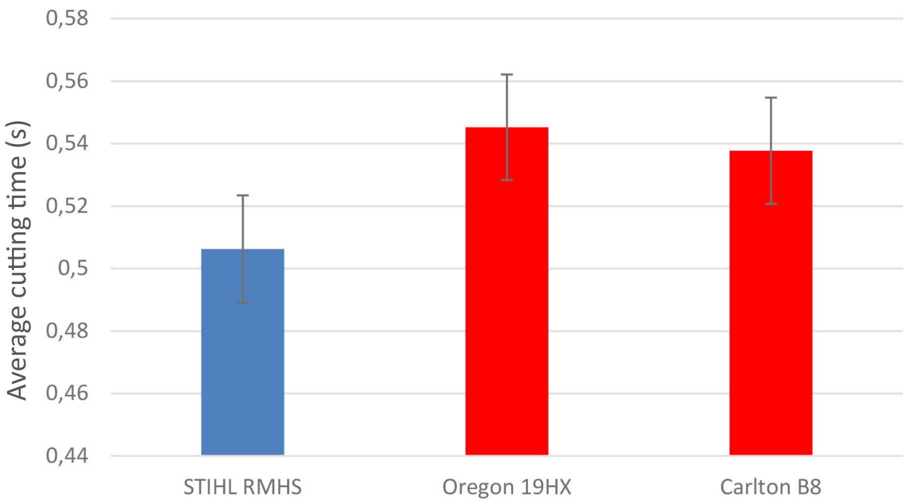

Figure 15. Average cutting time (least square means) of the new chains, with a 95-percent confidence interval. Chains with different colours are statistically differentiated with a very high level of confidence ($p < 0.0001$). Note that the y axis is truncated.

Figure 16 shows the association between cutting capacity and cut area for the chains. Cutting capacity (cm^2/s) is calculated from the associations between cutting time and cut area (Appendix 2). Like the results from previous studies, all chains showed a rapid initial increase in cutting capacity for small cut areas, followed by a slow increase towards an asymptotic value for larger cut areas.

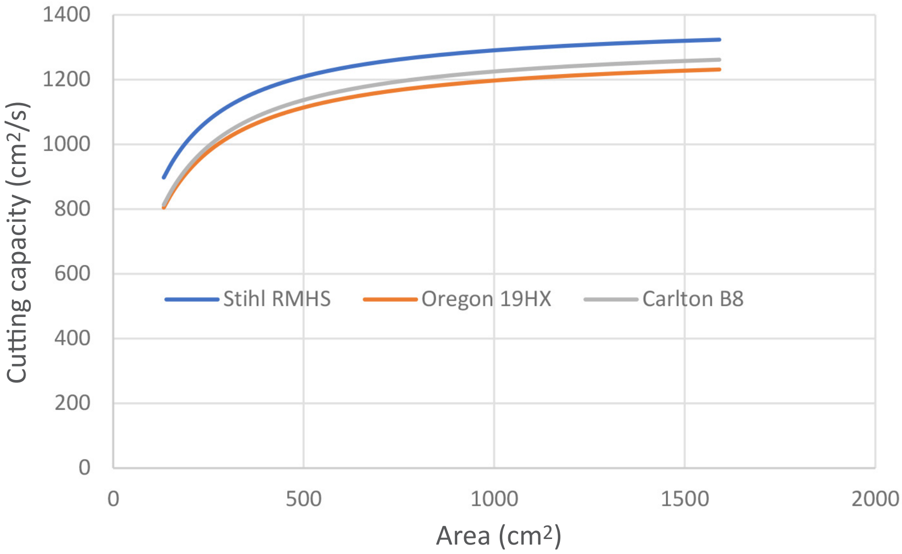

Figure 16. Association between cut area and cutting capacity for the new chains.

To facilitate comparison of the chains' cutting capacity found in our study with that found in previous studies where the F11-iP saw motor was used, the cutting capacity was calculated for a cut corresponding to 1000 cm^2 (diameter approximately 36 cm). An example of such a comparison is shown in Figure 17. The relationship between the cutting capacity of the Stihl RMHS and Carlton B8 chains was similar in the two comparative studies carried out using the test rig in Sävar. However, the general level of the chains' cutting capacity was somewhat higher in our study.

The measured cutting capacities in our study were also compared with the cutting capacity of a Stihl RMH chain (the model before the RMHS). Measurements for the Stihl RMH chain were obtained from a study of a new harvester, when the chain was fitted in a C144 harvester head from Komatsu (Nordström et al. 2018). A previous study (Jönsson et al. 2016) indicates that the cutting capacity of the Stihl RMH chain is almost identical to that of the Carlton B8 chain. In the study of the Stihl RMH chain on the harvester, the cutting capacity was very similar to that shown for the Carlton B8 chain in our study on the test rig (Figure 17). From this comparison, we draw the conclusion that the cutting capacities measured on the test rig in Sävar should also be relevant for the cutting capacity obtained in cutting with a harvester when the corresponding chain model was used.

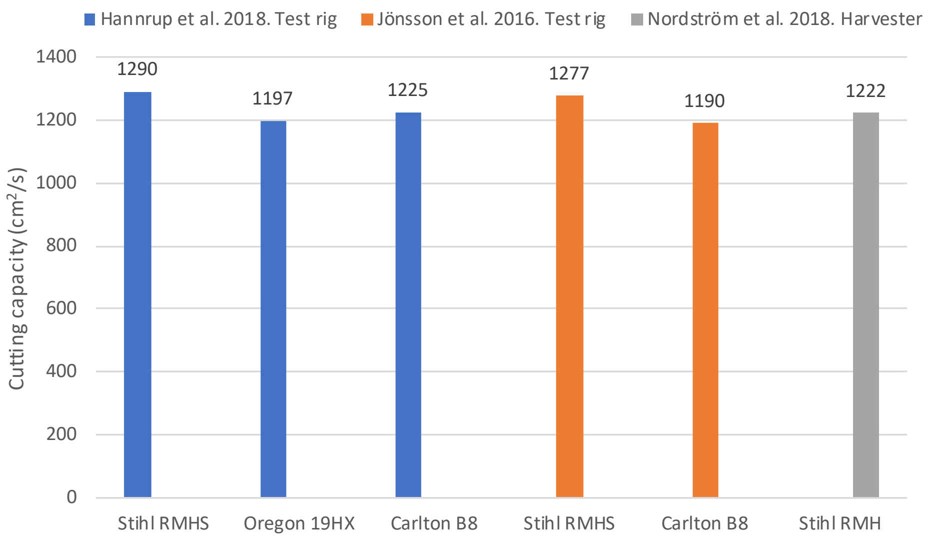

Figure 17. Comparison of results from studies of cutting capacity for saw chains performed on the test rig in Sävar (Hannrup et al. 2018, Jönsson et al. 2016) and on a harvester (Nordström et al. 2018).

In the comparison between the Stihl RMHS chain and the Oregon 19HX/Carlton B8 chains, the Stihl RMHS had a higher average rotation speed and a lower average torque and bar feed force (Table 4). All differences apart from one (the difference in rotation speed between the Stihl RMHS and the Carlton B8) were statistically significant with a very high level of confidence ($p < 0.001$). In an earlier study of rotation speed, torque and bar feed pressure in cutting with the Stihl RMHS and the Carlton B8, the same relationships were noted between the two chains (Jönsson et al. 2016), which supports the conclusion that there is a real difference between the chains in terms of these parameters in cutting with the particular saw motor.

Table 4. Least square means and standard error (S.E.) for the saw motor's rotation speed and torque, bar feed force and energy consumption, by chain model. Standard errors refer to the average mean error in paired tests of differences between chains.

	Cutting time (s)		Rotation speed (rpm)		Torque (Nm)		Bar feed force (N)		Energy consumption (kJ)	
Chain model	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
Stihl RMHS	0,506	0,0065	8673	10,2	39,0	0,3	358,5	7,1	18,9	0,5
Oregon 19HX	0,545	0,0065	8644	10,2	40,3	0,3	432,9	7,1	21,0	0,5
Carlton B8	0,538	0,0065	8658	10,2	39,9	0,3	417,3	7,1	20,6	0,5

In comparison with the Oregon 19HX and Carlton B8 chains. the Stihl RMHS chain had lower energy consumption over the entire diameter interval studied (Figure 18). The difference in energy consumption was greater than the difference in cutting time, and amounted to 11 percent (Oregon 19HX) and 9 percent (Carlton B8), respectively. In our study, energy consumption per cut was calculated by totalling the instantaneous output power of the saw motor over the cutting time. Instantaneous power was calculated on the basis of measurements of torque and rotation speed during the cutting process (Equation 1). The Stihl RMHS had a higher average rotation speed and lower average torque than the Oregon 19HX and the Carlton B8 chains. The differences between the chains was considerably larger for torque than for rotation speed, and we interpret the higher relative difference between the chains for energy consumption than for cutting time as an effect of this.

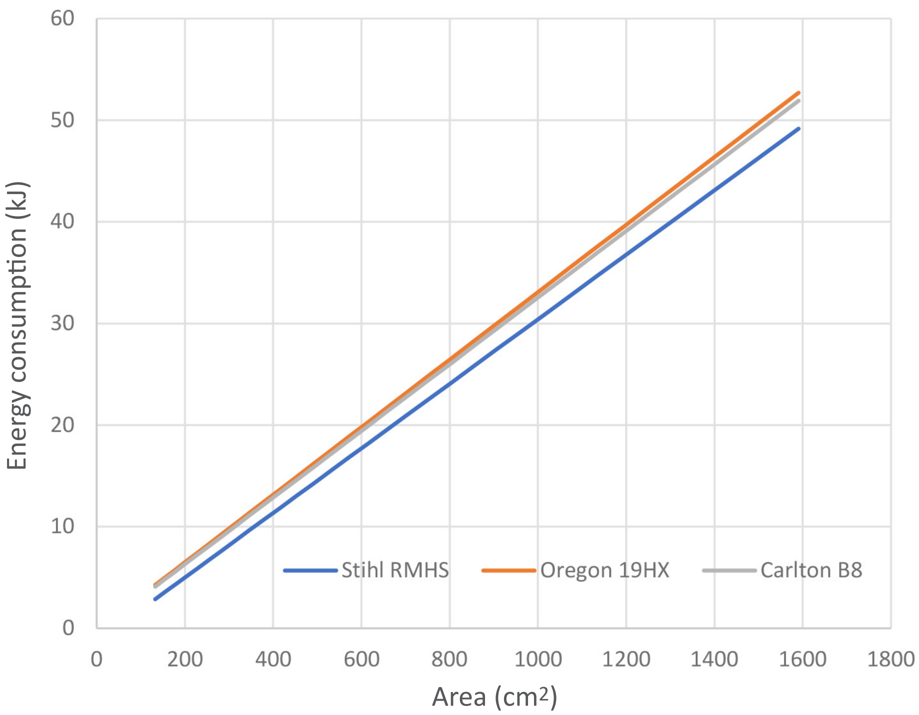

Figure 18. Regression lines for the association between cut area and energy consumption for the new chains.

EVALUATION OF THE SKIP CHAIN

The study included a skip chain, which was basically a modified Stihl RMHS chain. The skip chain had two drive links between each cutting tooth, so the number of cutting teeth was reduced by one-third. The skip chain was compared with a Stihl RMHS chain with a full set of cutting teeth. The skip chain had a longer cutting time over the entire diameter interval studied (Figure 19). The cutting capacity of a chain can probably be described as a balance between the cutting capacity and the ability to evacuate the chips and other debris. A hypothesis ahead of the study was that this evacuation could be a limiting factor, and that, by reducing the number of cutting teeth, evacuation of chips and other debris would be improved, and thereby reducing the cutting time. However, the result showed the opposite, and an interpretation of the longer cutting time for the skip chain is that the reduction in the number of cutting teeth caused a greater reduction in cutting capacity than the corresponding potential increase in the chain’s ability to evacuate chips.

To evaluate the effect of reducing the number of cutting teeth, the only thing changed on the skip chain was the number of cutting teeth. A possible and relevant modification might have been to increase the depth gauge setting compared with the original chain, the RMHS. With a greater depth gauge setting, every cutting tooth takes a larger proportion of chips, so could fill the increased spacing for evacuation.

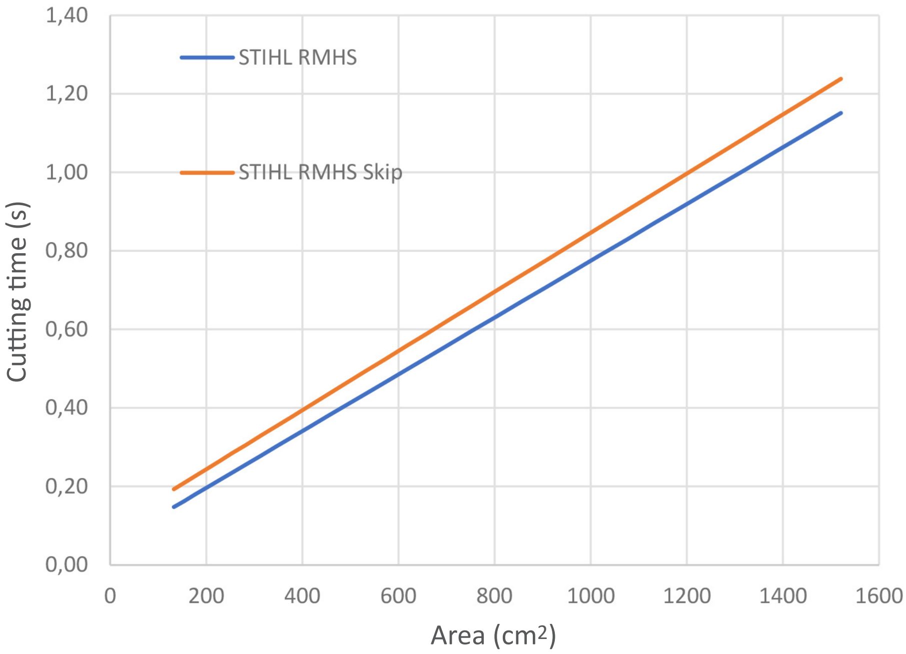

Figure 19. Regression lines for the association between cut area and cutting time for the skip-type chain and the corresponding chain with a full set of cutting teeth.

The skip chain had a lower rotation speed and a higher torque and energy consumption than the corresponding chain with a full set of cutting teeth (Table 5). However, the most noticeable difference was in the bar feed force, where the skip chain used nearly 50% greater force. The skip chain has a smaller number of teeth engaged in cutting, and the higher bar feed force for this chain indicates that the saw motor used (the Parker F11iP) has increased the bar feed force to reduce the rotation speed. The skip chain has fewer teeth engaged in cutting, so the cut should be easier. This is also why these types of chains are used in other situations.

Table 5. Least mean square values and standard error (S.E.) for the saw motor's rotation speed, torque, bar feed force and energy consumption, by chain model. The standard errors refer to the average standard error in pairwise tests of differences between the chain models.

	Cutting time (s)		Rotation speed (rpm)		Torque (Nm)		Bar feed force (N)		Energy consumption (kJ)	
Chain model	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
Stihl RMHS Skip	0,568	0,0065	8653	10,2	40,1	0,3	535,9	7,1	21,9	0,5
Stihl RMHS	0,506	0,0065	8673	10,2	39,0	0,3	358,5	7,1	18,9	0,5

In summary, our results show that the skip chain had 12 percent longer cutting time, 16 percent higher energy consumption and used 49 percent higher bar feed force than the corresponding chain with a full set of cutting teeth. From this, we conclude that skip chains have no advantages over conventional chains when they are used in combination with the saw motor in question, the F11iP.

COMPARISON BETWEEN THE REGROUND CHAINS

Figure 20 shows the average cutting times for the reground Carlton B8 chains and the new Carlton B8 chain (see Table 2 for a description of how the chains were ground). In general, the results showed only small differences in cutting time between the reground chains.

Chain 7 deviated most in terms of cutting time. This chain had the shortest cutting time of all chains, and the difference in cutting time compared to the new Carlton B8 chain (Chain 4) and the other reground Carlton B8 chains was statistically significant except for in relation to Chain 11. Chain 7 had almost identical grinding parameters as the chain tested by Jönsson et al. (2016), i.e. higher filing and cutting angles and a higher depth gauge setting than the new chain. However, unlike the chain in the earlier study, this chain had no grinding at the bottom of the teeth (see Figure 3).

In our study, the cutting time for Chain 7 was approximately 2 percent shorter than the new chain of the same model. In the earlier study, the corresponding difference between the chains was considerably greater (9 percent). We assume that the greater differences in cutting time found in the earlier study was caused by the reground chain having more grinding at the bottom of the teeth, which may have strengthened the effect of the chain's more aggressive grinding pattern. This assumption is supported by the finding in our study that grinding of the bottom part of the cutting teeth had a favourable effect on the cutting time. This was shown by Chain 11, which only differed from the new chain in the grinding near the bottom of the teeth, tending to have a shorter cutting time than the new chain (Figure 20). The cause of the favourable effect of grinding at the bottom part of the teeth cannot be identified by our study. However, a probable explanation is that the grinding near the bottom of the teeth increased the chain's ability to evacuate chips, by increasing the spacing for chip evacuation at the entry point under the cutting tooth.

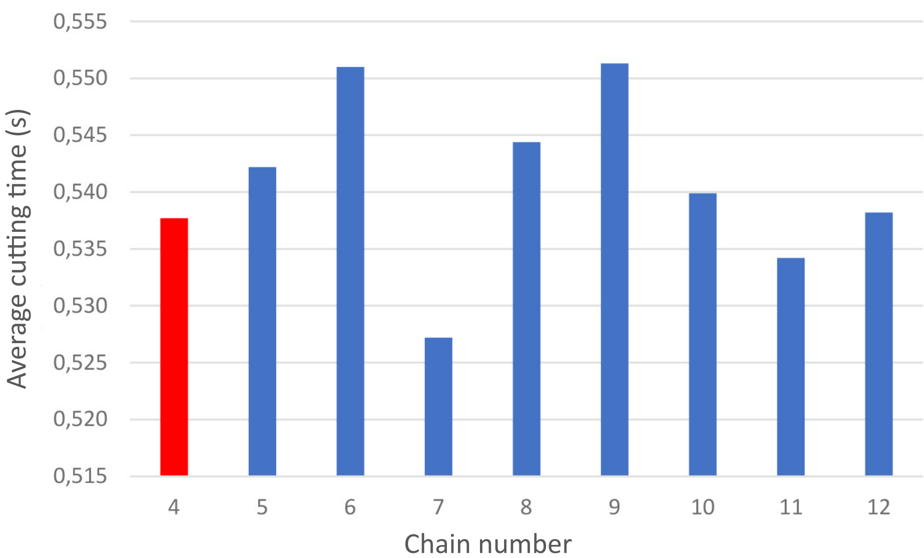

Figure 20. Average cutting time (least square means) for the reground Carlton B8 chains and for the new Carlton B8 chain (red bar). Note that the y axis is truncated. See Table 2 for a description of how the chains were ground.

The two chains that were ground with the grinding companies' standard settings (Chains 5 and 6) both had longer cutting time than the corresponding new chain (Chain 4), but only the difference in relation to Chain 6 was statistically significant. No statistically significant difference in cutting time was found between the two chains with standard grinding. They also differed in a number of parameters, such as the type of grinding wheel (ceramic and CBN wheel), grinding angle and depth gauge setting. From these results, we conclude that the standard grindings used in our study produce similar or somewhat longer cutting time than for the corresponding new chain.

The intention for Chains 8-11 was that the grinding would only change one parameter at time regarding the cutting teeth (filing angle, cutting angle, depth of grinding at the bottom part of the teeth, and depth gauge setting) compared with the new Carlton B8 chain (Chain 4), thereby isolating the effect of each of these parameters. However, this was not completely successful and, together with the small differences in cutting time between the chains (maximum slightly over 4 percent), no definitive conclusions could be drawn. However, the tendences we observed in our results are that the parameters that have a favourable effect on the cutting time are:

- **i)** greater filing angle in combination witn increased cutting angle,
- **ii)** greater depth gauge setting, and
- **iii)** grinding of the bottom parts of the cutting teeth.

These observations are supported by the following comparisons between the chains.

- **i)** Chain 8 with high filing and cutting angles had shorter cutting time than Chain 9, which only had a higher cutting angle. The chains had similar depth gauge settings.
- **ii)** Chain 10 had somewhat shorter cutting time than Chain 5, which had the same filing and cutting angles but a somewhat lower depth gauge setting. In addition, there was a general negative association between cutting time and depth gauge setting among the reground chains (Figure 21).
- **iii)** Chain 11 had shorter cutting time than the new chain and the reground Chain 5. The biggest difference between these two groups of chains was that, on Chain 11, the bottom parts of the cutting teeth were ground.

In all cases, these tendencies are logical, even if they seem to have small effects on the cutting time. The tendency that changing the individual parameters in turn has a favourable effect on the cutting time is strengthened by the results for Chain 7, where both the filing and cutting angles, and the depth gauge setting, were modified. The reduction in cutting time was greater than for the chains where only one parameter was changed.

For Chain 12, the intention was to grind the cutting teeth down aggressively until they were in a condition that corresponded to the end of a chain's life. This chain had similar cutting times to the new chain. However, based on our data, conclusions cannot be drawn regarding the effects of the aggressive grinding, because this chain also had a greatly increased cutting angle and a lower depth gauge setting.

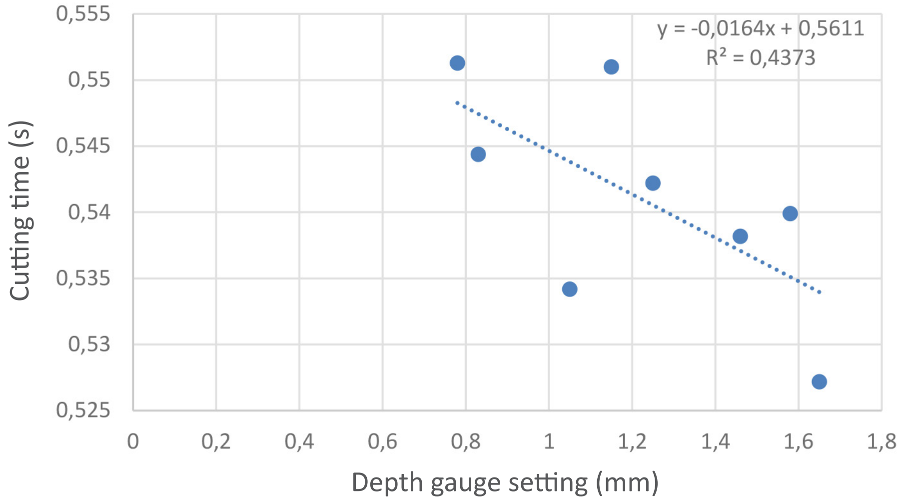

Figure 21. Association between depth gauge setting and cutting time for the reground chains. Note that the y axis is truncated.

Table 6. Least mean square values and standard error (S.E.) for the saw motor's rotation speed, torque, bar feed force and energy consumption, by chain. Standard errors refer to the average mean error in paired tests of differences between chains. See Table 2 for a description of the chains.

	Cutting time (s)		Rotation speed (rpm)		Torque (Nm)		Bar feed force (N)		Energy consumption (kJ)	
Chain no.	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**	**Mean**	**S.E.**
4	0,538	0,0065	8658	10,2	39,9	0,3	417,3	7,1	20,6	0,5
5	0,542	0,0065	8646	10,2	40,3	0,3	426,1	7,1	20,8	0,5
6	0,551	0,0065	8631	10,2	40,7	0,3	429,9	7,1	21,1	0,5
7	0,527	0,0065	8649	10,2	40,0	0,3	332,6	7,1	19,9	0,5
8	0,544	0,0065	8679	10,2	39,2	0,3	470,6	7,1	19,5	0,5
9	0,551	0,0065	8640	10,2	40,1	0,3	418,5	7,1	21,4	0,5
10	0,540	0,0065	8635	10,2	40,1	0,3	356,6	7,1	20,8	0,5
11	0,534	0,0065	8637	10,2	40,4	0,3	408,5	7,1	20,5	0,5
12	0,538	0,0065	8661	10,2	39,9	0,3	410,0	7,1	20,4	0,5

The saw motor used in the study (F11iP) is adjusted to a rotation speed corresponding to a chain speed of 40 m/s by regulating the bar feed force. Among the reground chains, there was considerable variation in bar feed force (Table 6). The difference between the chain with the lowest/highest bar feed force was 138 N. Among the measured grinding parameters in our study, the depth gauge setting showed the strongest association with the bar feed force (Figure 22).

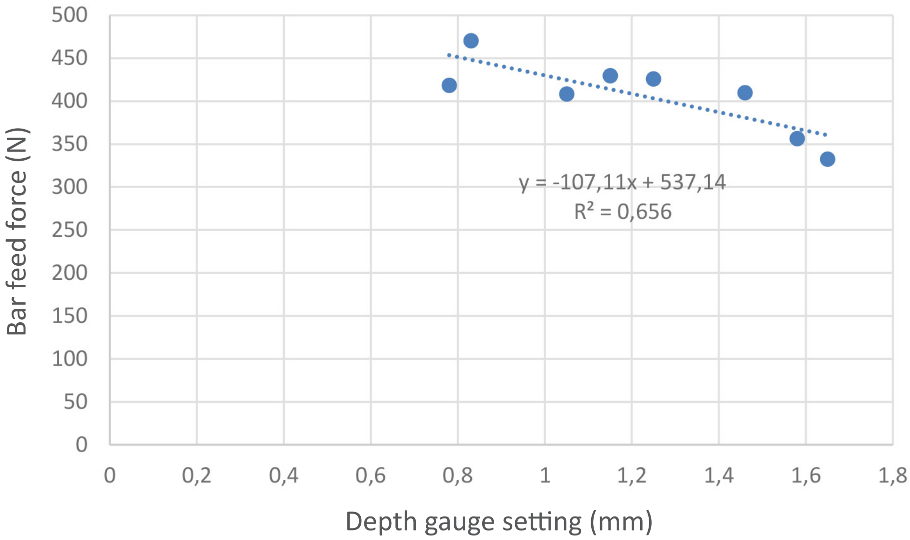

Figure 22. Association between depth gauge setting and bar feed force for the reground chains.

Conclusions

- Among the three new chains evaluated, the performance of the new Oregon 19 HX chain was similar to that of the Carlton B8 chain in terms of cutting time and energy consumption during the cutting process. The Stihl RMHS chain had shorter cutting time (approximately 7 percent), lower energy consumption (approximately 10 percent) and lower bar feed force (16-21 percent) than the Oregon 19 HX and Carlton B8 chains.
- The differences between the new Stihl RMHS chain and the Carlton B8 were similar, in line with the findings in a previous study (Jönsson et al. 2016).
- The evaluated skip chain of the full-skip type had 12 percent longer cutting time and used 49 percent higher bar feed force and 16 percent higher energy consumption than the corresponding chain with a full set of cutting teeth. This means that the skip chain showed no advantages compared with conventional chains in cutting, when it was used in combination with the F11iP saw motor.
- The differences in cutting time between the reground chains were generally small, but the results indicated that:
    - Standard grinding gives similar or somewhat longer cutting time than the corresponding new chain.
    - The parameters that had a favourable effect on the cutting time were a greater filing angle in combination with a higher cutting angle, a lower depth gauge setting, and more aggressive grinding at the bottom part of the cutting teeth. The biggest effect on the cutting time was attained for the chain with higher filing and cutting angle in combination with a lower depth gauge setting.

The study shows that, within the framework of current cutting tooth geometries, there is a potential to shorten the cutting time by modifying the grinding pattern, but this potential is limited.

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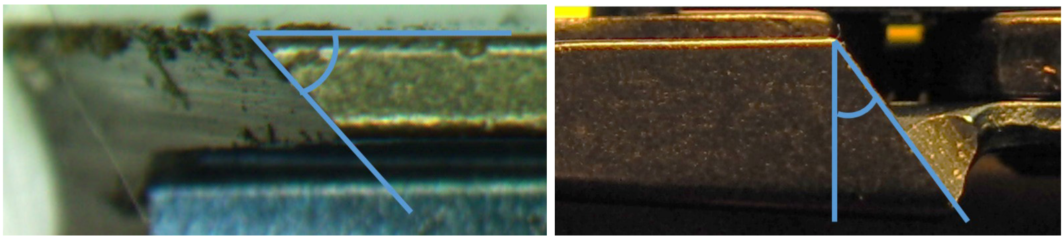
Appendix 1.

Definition of the angles measured on the cutting teeth.



Definition of the angles measured on the cutting teeth: cutting angle (left) and filing angle (right).

Appendix 2.

Regression equations for the associations between cut area and cutting time for the new chains.

Regression equations for the associations between cut area and cutting time for the new chains.

Chain no.	Regression equation[1)]
Stihl RMHS	Cutting time = 0,0519 + 0,000723 x cut area
Oregon 19HX	Cutting time = 0,0623 + 0,000773 x cut area
Carlton B8	Cutting time = 0,0632 + 0,000753 x cut area

1) The cut area is expressed in cm^2 and the cutting time in seconds