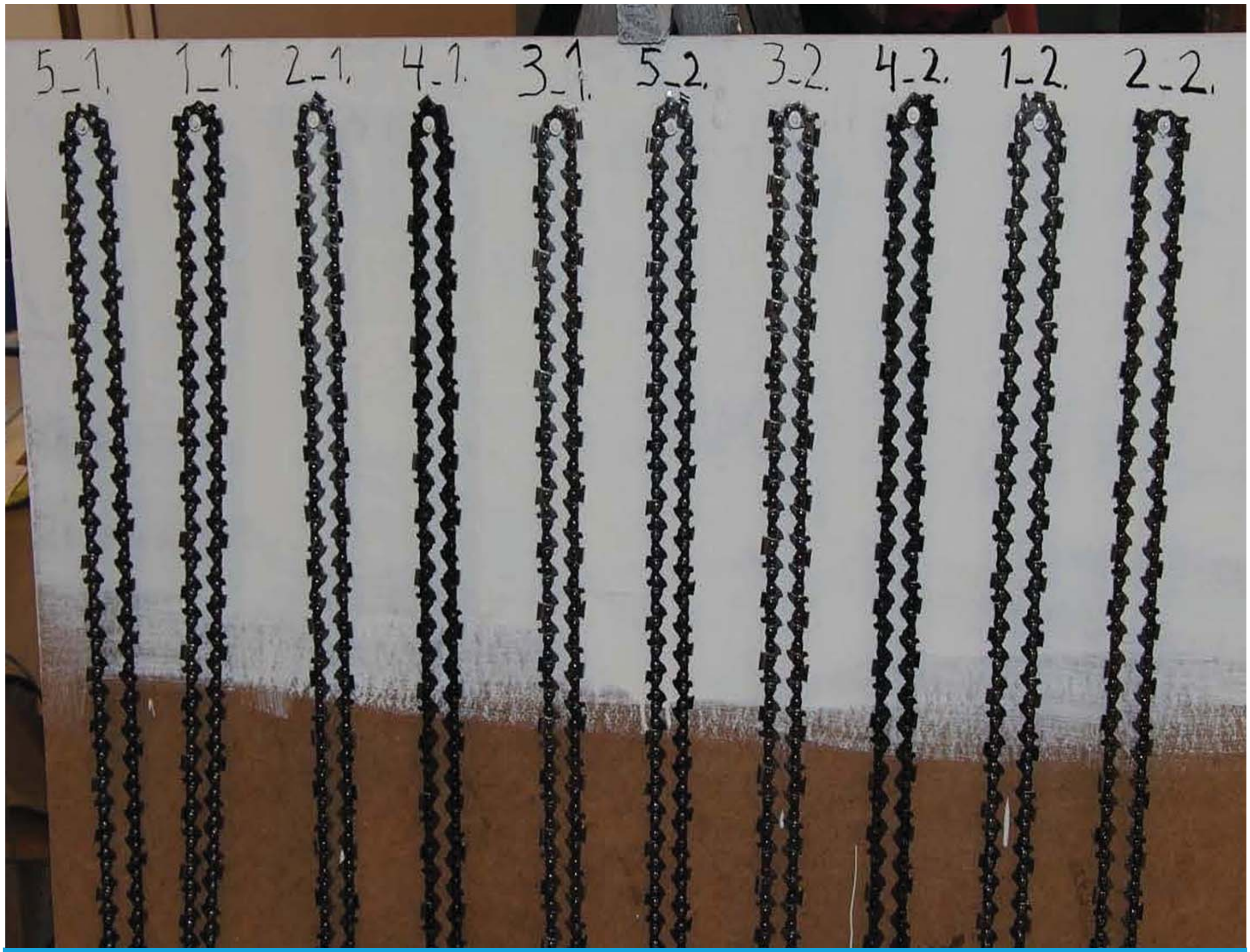

Arbetsrapport

Från Skogforsk nr. 918–2016

Cutting capacity of saw chains – a comparative study

Avverkningskapacitet för sågkedjor – en jämförande studie

Petrus Jönsson, Mikael Andersson, Björn Hannrup, Fredrik Henriksen, Anders Högdahl

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Arbetsrapport

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In the Arbetsrapporter series,
Skogforsk presents results and
conclusions from current projects.
The reports contain background
material, preliminary results,
conclusions, and analyses
from our research.

Titel:
Cutting capacity of saw chains
– a comparative study.

Avverkningskapacitet
för sågkedjor – en jämförande studie.

Bildtext:
The saw chains that
were evaluated in the study.

Ämnesord:
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Abstract

The aim of the study was to identify any differences in basic cutting capacity and energy consumption between the most common saw chain models on the market. Another aim was to examine whether sharpening brand new chains would have any effect on cutting time and energy consumption. All trials were carried out on the test rig built up at Skogforsk in Sävar.

The results revealed that the brand new chains varied by approximately 6% in terms of cutting time and energy consumption. The resharpened chain had a shorter cutting time (9%) and lower energy consumption (10%) than corresponding brand new chains. All these differences were statistically reliable with a very high degree of certainty.

Foreword

This report summarises the results from the study *Cutting capacity of saw chains - a comparative study*. The study was financed through Skogforsk's technology initiative 2016 and by the funding foundation, Södras Stiftelse för Forskning, Utveckling och Utbildning.

Ljusdals sliptjänst sharpened the saw chains used in the study. Iggesund Forest, STIHL and Svenska Blount provided the new saw chains tested in the study. Sveaskog provided the logs used for cutting slices.

The following were project contacts at the various companies:

Name	Company
Mats Nyberg	Ljusdals sliptjänst AB
Gustav Nyrén	Iggesund Forest AB
David Johnsson	Svenska Blount AB
Claes Kindblom	Sveaskog Förvaltnings AB

All measurements of cutting time and energy consumption were carried out on the test rig built up at the Skogforsk facility in Sävar. Komatsu Forest provided a harvester head, a hydraulic power unit, and expertise regarding the harvester head. Parker Hannifin provided an F11-iP saw motor and expertise regarding its adjustment. Mikael Andersson, Fredrik Henriksen and Anders Högdahl, Skogforsk, built and adjusted the test rig.

A working group from Skogforsk, comprising Mikael Andersson, Fredrik Henriksen, Björn Hannrup and Petrus Jönsson, carried out measurements and analysed the data. Fredrik Henriksen developed the algorithms used to determine cutting time from torque measurements of the saw motor during the cutting process.

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

A big 'thank you' to all involved!

Uppsala, 29 September 2016

Petrus Jönsson and Björn Hannrup

Contents

Summary

Cutting stems is a key component in the work of a harvester, and measures that help shorten cutting time could potentially have a positive effect on both harvester productivity and wood value. One crucial factor affecting cutting time is the cutting capacity of the saw chain. There are currently no published studies that use objective data to examine cutting capacity and energy consumption of machine saw chains.

The aim of this study was to identify any differences in basic cutting capacity and energy consumption between the most common saw chain models on the market. Another goal was to examine whether sharpening new chains has any effect on cutting time and energy consumption. The study was limited to cutting fresh, unfrozen wood from Norway spruce. All measurements were carried out on the test rig built up at Skogforsk in Sävar.

New chains of the saw chain models Carlton B8, STIHL RMH, STIHL RMHS and Oregon 18HX were evaluated in the study. For each model, two chains were used, taken from different manufacturing batches. For one of the chain models, Carlton B8, measurements were also taken after the chains had been sharpened by Ljusdals sliptjänst, using the company's ordinary method for sharpening.

Measurements were taken during the cutting of slices from six spruce logs with diameters in the interval 127 to 377 millimetres. Measurements were taken from 23 cuts per chain, i.e. 46 cuts per chain model. Energy consumption was determined by measuring the torque and revolution speed of the output shaft of the saw motor during the cutting process. Information about the saw motor's torque was also used to determine the cutting time, using algorithms that identified the start and stop times for the cut through the stem.

The results from the measurements can be summarised as follows:

- The new chains, Carlton B8, STIHL RMH and Oregon 18HX, had almost identical cutting time and energy consumption. The STIHL RMHS had shorter cutting time (~6 percent) and lower energy consumption (~7 percent) than the other three new chains. These differences were statistically significant with a very high degree of certainty.

- The sharpened Carlton B8 chain had shorter cutting time (~9 percent) and lower energy consumption (~10 percent) than the new Carlton B8 chain. These differences were statistically significant with a very high degree of certainty.

- The bar feed pressure in cutting was lower for the STIHL RMHS and the sharpened Carlton B8 chain than for the other three new chains. The difference was approximately 6 percent and was statistically significant with a high degree of certainty.

- The test rig, in combination with the method used, proved to be effective in taking measurements from a limited data set to detect differences between treatments.

Our study showed that cutting time and energy consumption differed between the most common chain models, and that sharpening, using the method applied by Ljusdals sliptjänst, had a favourable effect on all parameters. The observed effects of chain model and sharpening were so great that they should have a considerable effect on productivity and fuel consumption when logging with a harvester. However, new studies are needed to examine effects on wear, for example if the natural blunting of the chain occurs at different rates for different chain models/sharpening.

Introduction

Cutting tree stems is a key component in the work of a harvester, comprising 7-11 percent of the effective work (T. Brunberg, pers. comm., 2015, unpublished follow-up based on harvester machine data), so cutting time has a significant effect on harvester productivity. Furthermore, an association has been found between cutting time and the occurrence of bucking splits (Hannrup & Jönsson, 2010). Measures that help to shorten cutting time therefore have potential to improve both harvester productivity and wood value.

How has cutting time on harvesters changed over time?

Few published studies have examined this, but comparable data can be found in the Timber Value Test 2001 (Hallonborg & Granlund, 2002) and in a recent study of saw motors (Jönsson et al., 2014). In both cases, unfrozen spruce wood was cut with new, correctly adjusted harvester heads. Comparison of data from the two points in time indicates that harvester cutting time has been reduced by approximately 10 percent over the period. This corresponds to a productivity increase of 0.7 to 1.1 percent for the effective work of the harvester, leading to an annual saving in costs of SEK 26 to 42 million for Swedish forestry. A corresponding increase in productivity through shortened cutting times could be possible in the future, but this will require dedicated development work.

One crucial factor affecting cutting time is the cutting capacity of the saw chain. Chains for chain saws were introduced in the 1940s, and have since developed with a similar design (see presentation of history in Stacke 1989), even if chains have been continually improved. Applied studies on machine saw chains have mainly focused on economic aspects (Dahlström & Helgesson, 1992) and aspects regarding chain shot (Hallonborg, 2003; Johansson et al., 2004). To the best of our knowledge, there have been no studies published that use objective data to try to highlight the cutting capacity and performance of machine saw chains. This type of study is vital in disseminating objective information to chain users, and thereby indirectly for stimulating development in the manufacturing companies.

One reason for the lack of comparative studies of the cutting capacity of machine saw chains is probably the experimental difficulties associated with studies of the rapid processes involved in cutting. However, a test rig has recently been built up at Skogforsk in Sävar, comprising a hydraulic power unit and a harvester head, suspended in a steel frame. The frame is fitted with a series of sensors that measure parameters relevant to the cutting process, such as the saw motor's torque and speed, bar position and pressure, and flow and temperature of hydraulic oil in different positions. The test rig offers unique opportunities for studies in a controlled environment of cut-related equipment through collection of detailed, relevant measurements.

What evidence is there that differences occur in cutting capacity between the saw chains currently available on the market?

There is currently no published, statistical data that can illustrate differences in cutting capacity between saw chains of different models. However, an indication that differences occur is provided by limited measurements of chains from two manufacturers carried out at Skogforsk's test rig in Sävar (P. Jönsson and B. Hannrup, pers. comm. 2015). Another indirect indication of potential to improve cutting capacity is that many harvesting teams always sharpen new chains before they are used for the first time, because the operators feel that this increases the cutting capacity of the chains (E. Edwinsson, pers. comm. 2015). However, there is currently no objective data that shows whether this procedure does affect the cutting capacity of the saws.

Objectives and scope

The overall objective of the measures in the project is to help reduce cutting time, and thereby increase harvester productivity and the value of the cut wood.

The aim of the study was to identify any differences in basic cutting capacity and energy consumption between the most common saw chain models on the market. The specific goals were:

- To carry out measurements in a controlled environment of cutting time and energy consumption for new machine saw chains from leading manufacturers.
- To examine how sharpening new chains affects cutting time and energy consumption.

The study was limited to cutting fresh, unfrozen wood of Norway spruce. The study was also limited to examining cutting capacity of new and sharpened new chains. The effect of wear on the performance of the studied chains lay outside the limits of the study.

Materials and methods

EXPERIMENTAL DESIGN

In the study, an evaluation was carried out of new chains from the four most common saw chain models on the market at the time of the study (Table 1). On one of the chain models, Carlton B8, measurements were also taken after sharpening to enable an analysis of the effect of sharpening. Ljusdals sliptjänst sharpened the chains using its ordinary method. All chains evaluated had 96 drive links and a gauge of 2.0 mm.

Table 1.
Experimental setup in the evaluation of new and sharpened chains from the four studied chain models.

Chain category	Manufacturer	Model	Treatment	Chain number	Chain ID
New	Carlton	B8	1	1	1_1
New	Carlton	B8	1	2	1_2
New	STIHL	RMH	2	1	2_1
New	STIHL	RMH	2	2	2_2
New	STIHL	RMHS	3	1	3_1
New	STIHL	RMHS	3	2	3_2
New	Oregon	18HX	4	1	4_1
New	Oregon	18HX	4	2	4_2
Sharpened	Carlton	B8	5	1	5_1
Sharpened	Carlton	B8	5	2	5_2

In the study, the chain models were represented by five treatments (Table 1). For each treatment, measurements were taken on two chains on each model, from different manufacturing batches. We used two chains per model to obtain a more reliable determination of the individual chain model's performance. This enabled us to buffer, to a certain extent, for the possible variation that could occur between different manufacturing batches.

Figure 1.
Photo taken from behind the two types of cutting teeth found on the evaluated chain models: semi-chisel (left) and Chamfer chisel (right).

Three of the four chain models evaluated in the study had 'semi-chisel' cutting teeth, while the fourth (Carlton B8) had the 'Chamfer chisel' type (Figure 1, Table 2). The semi-chisel type has rounded corners, while the corners on the Chamfer chisel type are more angular.

The dimensions of the cutting teeth are shown in Table 2 (see Figure 2 for definitions of the measurements). The cutting teeth on the STIHL RMH and Oregon 18HX were of similar dimensions, and were narrower in both front and back edge compared with those on the Carlton B8 and STIHL RMHS (measurements A and B). STIHL RMHS and Carlton B8 had similar dimensions, apart from the length of the cutting teeth (measurement C), where the STIHL RMHS had longer teeth. This meant that the STIHL RMHS had a cutting tooth area (seen from above) that was approximately 20 percent bigger than the cutting tooth area for the other three chain models. STIHL RMHS was also the heaviest, even if the difference compared with two of the other chain models was not as great as for the chain area (Table 2).

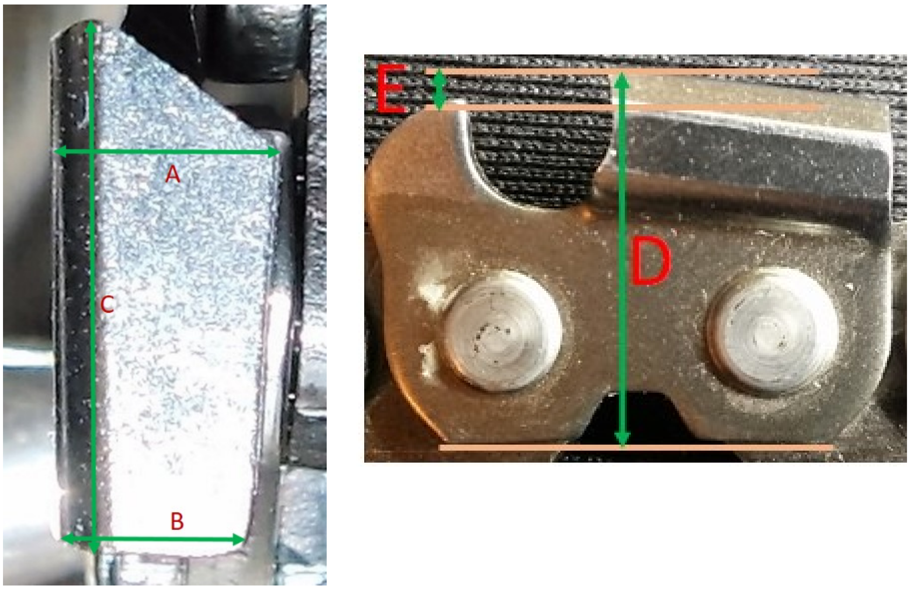

Figure 2
Photos illustrating the different dimension measurements used to describe the cutting teeth in the studied chain models.

Table 2.
Type of cutting tooth, dimensions of cutting teeth, and total weights of the evaluated chain models.

Chain model	Type of cutting tooth[1]	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	Weight (g)
Carlton B8	c.c.	5.4	4.9	10.8	15.0	1.2	787
STIHL RMH	s.c.	4.8	4.0	12.0	13.8	1.5	694
STIHL RMHS	s.c.	5.6	4.9	12.5	15.0	1.1	825
Oregon 18HX	s.c.	4.9	4.3	11.9	14.3	1.3	766
Sharpened Carlton B8	c.c.	5.4	4.9	9.9	14.7	1.6	776

[1] c.c. = Chamfer chisel, s.c. = semi-chisel.

Table 3 shows the filing and cutting edge angle of the cutting teeth in the evaluated chain models. In the study, the angles were measured by taking photos of the chains with a stereo microscope (Nikon SMZ1270) with a built-in camera (DeltaPix Invenio 10S III). The angles were then measured on the photos using the Photron FASTCAM Viewer software. Appendix 1 shows definitions of the measured angles, and Appendix 2 shows pictures of the cutting teeth for all evaluated chain models.

Table 3.
Filing and cutting edge angle of the cutting teeth in the evaluated chain models. See Appendix 1 for a definition of the angles.

Chain model	Filing angle (°)	Cutting edge angle (°)
Carlton B8	32	44
STIHL RMH	28	43
STIHL RMHS	35	36
Oregon 18HX	35	46
Sharpened Carlton B8	43	36

The four models evaluated with new chains had cutting teeth with similar filing and cutting edge angles (Table 3, Appendix 2). The exception was the STIHL RMHS, where the cutting edge angle was 19-28 percent smaller than the other three chain models. The sharpened Carlton B8 chain had a considerably higher filing angle and lower cutting edge angle than the new version of that chain model. The differences were 11 and 8 degrees respectively.

MATERIAL

All measurements were taken during cutting of stem slices in Skogforsk's test rig in Sävar (see section 'Main components of the test rig'). The slices were cut from six spruce logs with diameters varying between 127 and 377 millimetres (Figure 3). The broad diameter interval was chosen to find the general relationship between cutting time and cut area, and between energy consumption and cut area. The logs were cut at both ends to obtain a good diameter distribution from a limited number of logs. For butt logs, the first half metre was cut off the butt end, because this part of the stems was often oval.

Figure 3.
Spruce logs used for cutting of slices. In the picture, the original six logs have been cut in the middle to facilitate cutting in both log ends.

From each log end, the measurement values from two cuts per chain were recorded. For one log end, only one cut per chain was recorded. This resulted in a total of 23 cuts per chain over the studied diameter interval. This gave measurements from a total of 46 cuts per treatment, because there were two chains in each treatment. The internal cutting order between the chains for the cut in the top ends of the logs was drawn by lots (Figure 4). When cutting the butt ends of the logs, the reverse order was used, in order to create as big a variation in log diameter as possible for each chain.

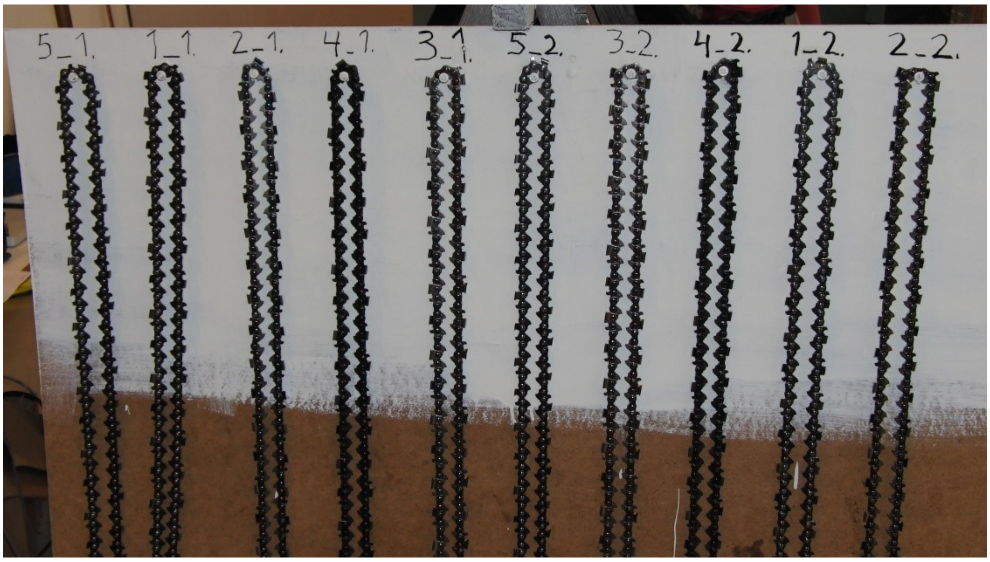

Figure 4.
The saw chains in the study were suspended in an order drawn by lots for cutting in the top ends of the logs. The chains are marked with treatment and chain number as shown in Table 1.

Logs were obtained from a nearby logging site and, to reduce the risk of drying, the time from felling to measurement was as short as possible. To check for any drying, moisture content was recorded for six of the slices used in the study. Three of the slices were the first slices cut from a log end (outer slices), while the other three were cut as the inner slices in the same log ends (inner slices). The moisture content of the slices was calculated from weighing data at the time of the study, and after seven days of drying at 105°C. The average moisture content of the slices was 51 percent, which is the same moisture content as fresh wood that can be expected based on existing functions for predicting moisture content (Wilhelmsson & Moberg, 2004). Furthermore, there was no indication of any difference in moisture content between the outer and inner slices cut from the same log end. From these measurements, we conclude that, at the time of the study, the logs could be regarded as fresh, with negligible effect of drying.

Main components of the test rig

All slices were cut in Skogforsk's test rig in Sävar. The test rig comprised a Komatsu 360.2 harvester head from Komatsu Forest, suspended in a steel frame (Figure 5). To ensure a high level of safety, while enabling filming and visual surveillance of the cutting process, the frame was fitted with walls of steel plate and safety glass.

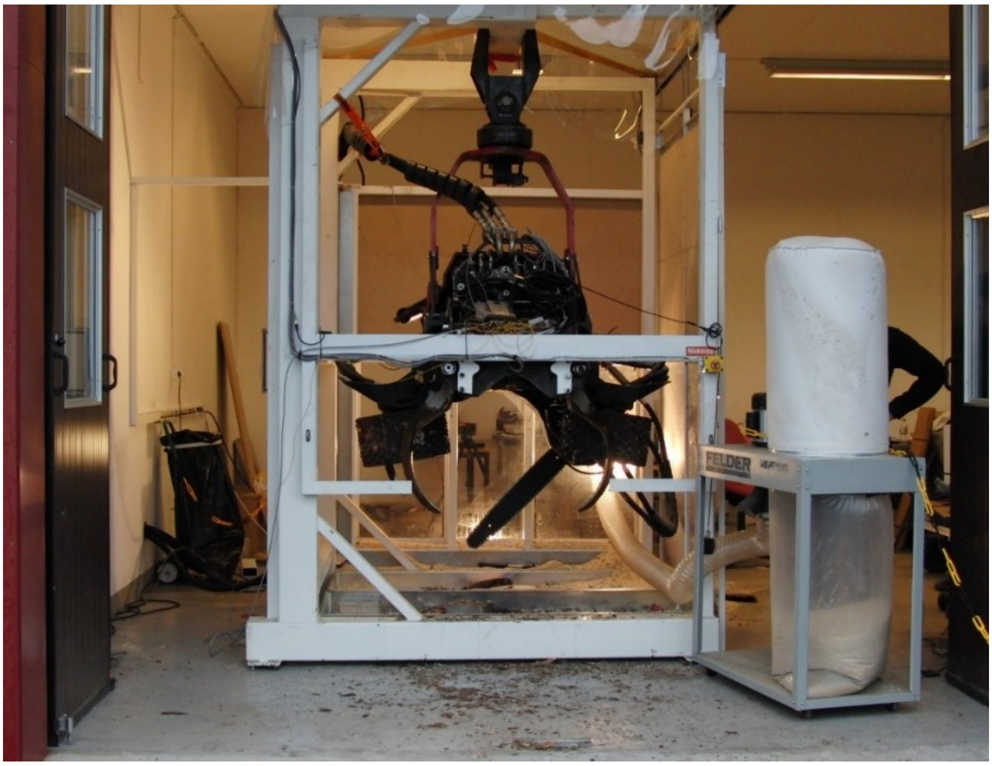

Figure 5.
Harvester head suspended in a steel frame.

The main components of the associated hydraulic system were:

- A Sisu diesel engine placed in a separate area (Figure 6).
- Two variable load sensing axial piston pumps (Brueninghaus Hydromatik, now Bosch Rexroth) with a displacement of 145 and 130 cm^3/rotation respectively. During the study, only one of the pumps (130 cm^3/rotation) was used to operate the head.
- Hoses from hydraulic power unit to the harvester head. The hose length corresponded to the length of the hydraulic hoses in a conventional harvester.

The axial piston pump delivers a specific flow based on a certain control signal. This is done by regulating the angle of the swivel plate, which controls the stroke length of the pistons. The load sensing function (Figure 7) links the stroke (travel) position with the actual pressure in the system, and thereby educes the flow if the pressure becomes unnecessarily high, and increases the flow when the pressure is lower than required.

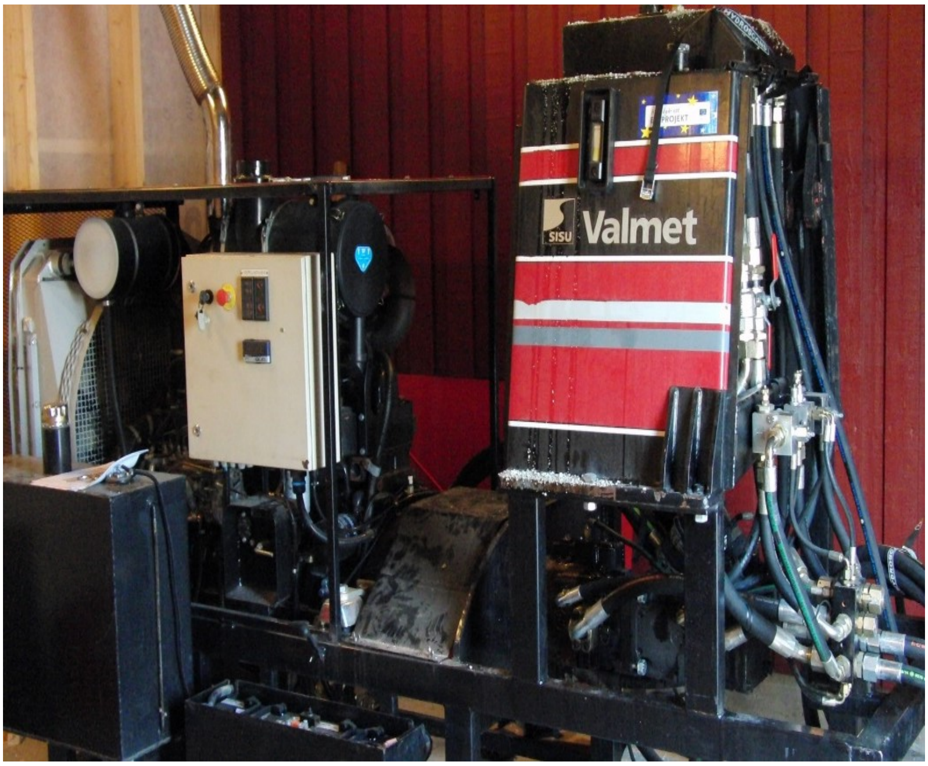

Figure 6.
The diesel engine of the test rig and associated hydraulic power unit.

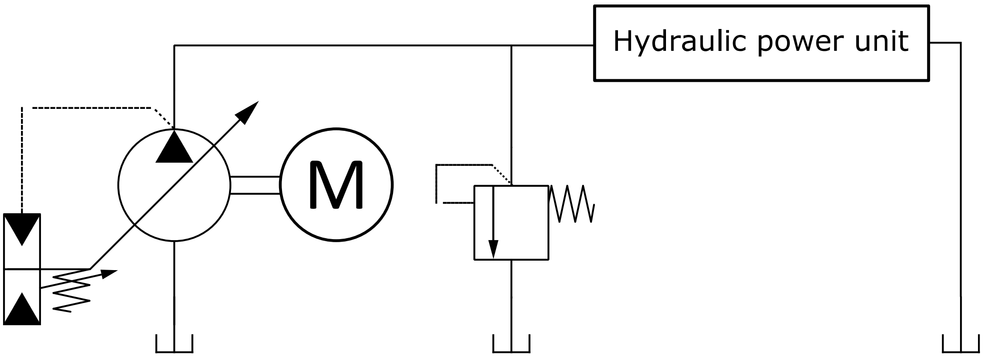

Figure 7.
Schematic illustration of the load sensing hydraulic system used in the study.

The hydraulic power unit and the harvester head were controlled using the Bodas RC-28-14/30 controller, made by Bosch Rexroth. The software was specially designed for the study in the Bodas Design program. A PC was used to communicate with the controller (PLC) through an interface. The controller regulates the valves to attain the desired movement. The sensors read off the system, send data to the controller, from where control currents and sensor data are sent to the PC for logging (Figure 8). When the data was logged on the PC, a sample time of 5 milliseconds was used for the controller.

The saw unit on the harvester head was based on the F11-iP saw motor from Parker Hannifin. A new motor was fitted for this study. The F11-iP has an integrated hydraulic control that allows the chain speed to be kept constant throughout the cutting process. This was achieved by using a constant-flow valve that limits the flow after the motor, resulting in an even flow and thereby an even number of revolutions.

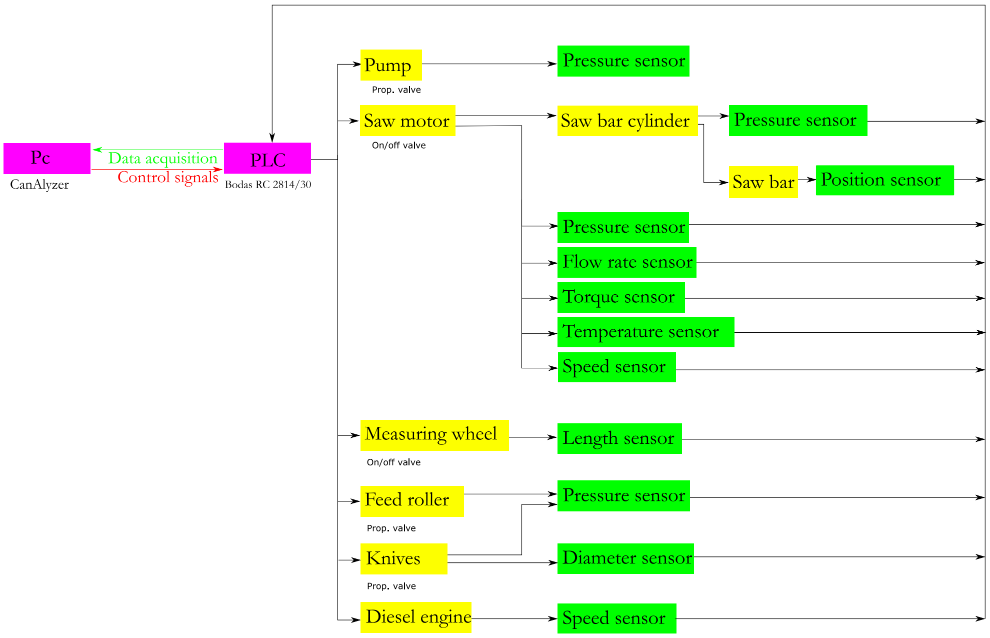

Figure 8.
Schematic diagram of data collection and control. The purple blocks indicates the computes, yellow blocks are functions and green are sensors/transmitters.

MEASUREMENTS DURING THE CUTTING PROCESS

The time for the cut through the stem was determined from transmitter data about the torque of the saw motor during the cutting process. This indirect method for determining cutting time showed very good correspondence with the cutting time determined by filming with the high-speed camera (see also the section 'Calculated variables and filtering of raw data').

The torque was measured with a torque transducer (T22 from HBM), which was fitted on the output shaft of the saw motor. To accommodate this sensor between the saw motor and the saw box, the head was modified by moving the saw box back and lengthening the saw motor's output shaft (shown by the red rectangle in Figure 9).

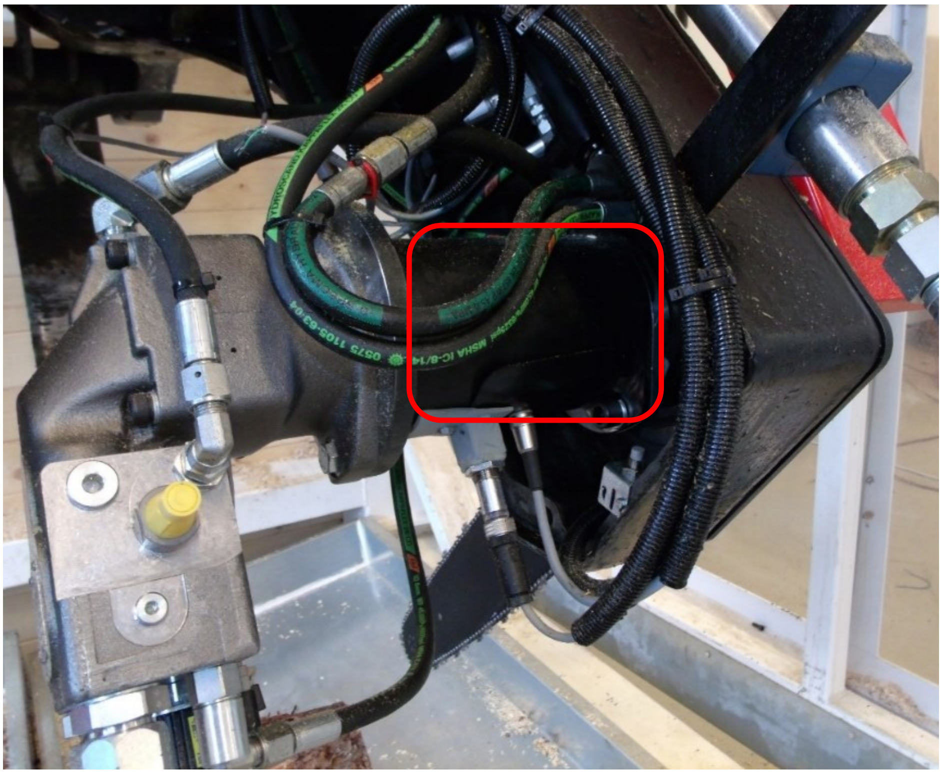

Figure 9.
Photo showing how the saw motor's output shaft was extended. In the lower part of the extension (marked with a red rectangle), the outlets for the torque transducer (right) and tachometer (left).

The revolutions of the saw motor were measured with an optical pulse encoder that was directed towards the extended part of the saw motor's shaft. The pulse encoder gave three pulses per revolution.

The flow, pressure and temperature of the hydraulic oil were measured with two flow rate transmitters fitted before and after the saw motor (Figure 10). On the flow rate transmitters (Hydac Electronic, EVS 3104), a temperature transmitter (Hydac Electronics, ETS 4144) and a pressure outlet were fitted. On the pressure outlet, a pressure transmitter (Hydac Electronics, HDA 4845) was fitted.

Pressure in the bar cylinder was measured by a pressure transmitter (Hydac Electronics, HDA 4845) fitted on the cylinder's plus and minus side. In our study, the difference in pressure between these transmitters gave an indirect measurement of the bar feed force during the cutting process.

Figure 10.
Transmitter fitted for measuring pressure, flow and temperature of the hydraulic oil before and after the saw motor.

OTHER MEASUREMENTS

Sawdust samples were taken to examine any differences in fraction size between the chains. A sample of approximately 0.5 dm^3 was taken during cutting by one of the two tested chains per treatment. The samples were taken when cutting in the same log. The samples were screened, using the following mesh sizes (mm^2): 8, 5.6, 4, 2, 1 (Figure 11). Each fraction size was weighed separately, and the proportions of the total dust amount by weight and fraction size were calculated.

Figure 11.
Screen, with bowls of varying mesh size. The screening bowl with a mesh size of 8 mm^2 is nearest the camera.

VARIABLES CALCULATED

Cutting time was defined as the time taken for the chain to cut through the stem. Previous studies indicate that calculating cutting time using the saw motor's torque allows a rapid, objective determination of this parameter (Hannrup et al., 2015). In our study, we adapted previously developed algorithms that use torque information to identify start and stop time for the cut through the stem (see Hannrup et al. (2015) for a description of the algorithms). The main changes involved creating the time-based window within which possible start points were sought for the cut in the stem.

The algorithms for determining cutting time using torque information were applied on previously collected data, which included filming the cutting process with a high-speed camera. A comparison between cutting time based on the high-speed filming (which was regarded as the 'correct' result) and cutting time based on torque showed a very high level of agreement (Figure 12). The systematic deviation was negligible (0.005 s) and the standard deviation between the two methods for determining cutting time was 0.01 s. This means that in 95 percent of cases, the cutting time based on torque information is expected to lie within 0.02 s of the cutting time shown by high-speed filming. We therefore conclude that determining cutting time based on information about torque, and by using algorithms, is an efficient method that can predict the true cutting time with great accuracy and precision.

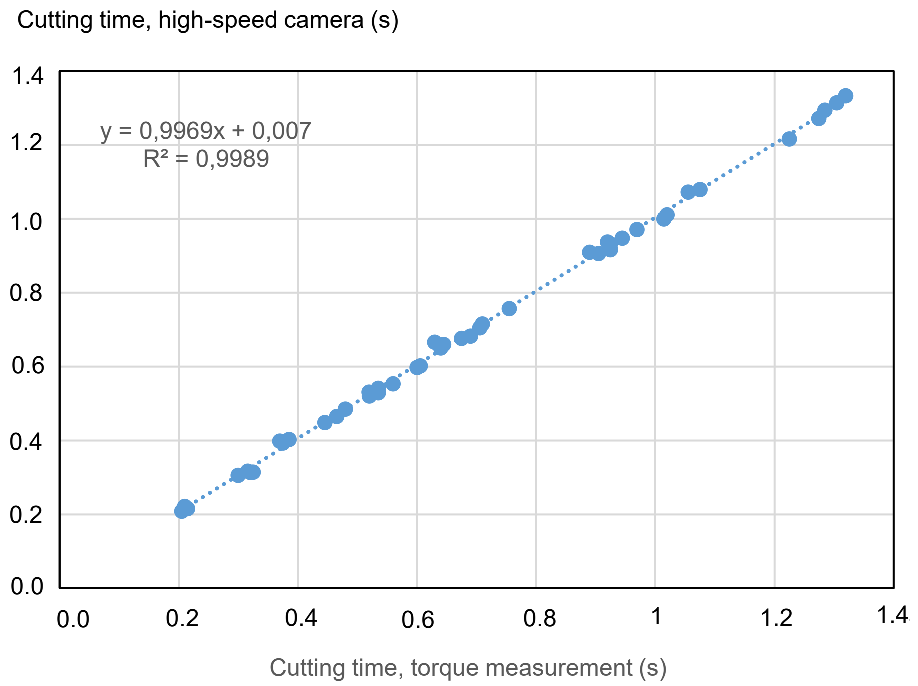

Figure 12.
Relationship between cutting times calculated through saw motor torque and filming with high-speed camera.

The saw motor's instantaneous output power during the cut (P), expressed in kW, was calculated as:

[1] $$P = T \cdot \omega /1000$$

where

T is the torque on the saw motor's output shaft expressed in newton-metres, and ω is the rotation speed of the saw motor's output shaft expressed in radians per second.

The total output energy from the saw motor per cut, expressed in kJ (E), was calculated by integrating the saw motor's instantaneous output power over the cutting time. This was done by summing the product of the average value between each adjacent measurement value for the saw motor's instantaneous output power and its time difference (Δt) as in the following equation. This was done as the controller's sample time was not completely constant.

[2] $$E = \sum_i \frac{P_{i+}P_{i+1}}{2} \cdot \Delta t_i$$

The means of the torque (μ_T) and rotation speed of the saw motor's output shaft (μ_ω) during the cut was obtained as a weighted mean by dividing integration by the total cutting time (t_{cut}) as follows:

[3] $$\mu_T = \frac{\sum_i \frac{T_i + T_{i+1}}{2} \Delta t_i}{t_{cut}}$$

[4] $$\mu_\omega = \frac{\sum_i \frac{\omega_i + \omega_{i+1}}{2} \Delta t_i}{t_{cut}}$$

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

[5] $$n = \omega \cdot \frac{60}{2\pi}$$

[6] $$v = n \cdot n_s \cdot \vartheta$$

where

n is the number of revolutions of the saw motor's output shaft expressed in revolutions per minute, n_s is the number of teeth on the sprocket (13) and ϑ is the chain pitch, which was 0.00034.

STATISTICAL ANALYSIS

Most of the cut-related parameters (such as cutting time and energy consumption) measured in the study were strongly correlated to the area of the cut slices. To test whether the differences between treatments for the cut-related parameters were statistically significant when differences in slice area were considered, a variance analysis was performed. The area of the cut slices was then used as a covariate in the analysis (i.e. to compensate for differences between treatments in terms of slice area). The following model was adapted:

[7] $$y = a + f + e$$

where

y is the cut-related parameter analysed, a the area of the cut slice, f the treatment, and e the random error. In the analysis, the least square mean for the treatment was calculated, i.e. the mean of the cut-related parameters after compensating for differences between treatments in terms of slice area.

EXCLUDED OBSERVATIONS

Three observations were excluded from cuts made by the chain models STIHL RMH, STIHL RMHS and Oregon 18HX. Two of the observations were excluded because the signal from the torque transmitter for the initial part of the cut was very noisy, making it impossible to detect the start point of the cut. The third observation was excluded because of a greatly increased cutting time (+20 percent).

Results and discussion

CUTTING TIME AND CUTTING CAPACITY

Figure 13 shows the linear relationship between cut area and cutting time. In the figure, all measurement values are shown, so the variation in cutting time at a certain cut area included all sources of variation that occurred, such as the variation between treatments, variation between chains in the treatment, and variation linked to the wood condition in the individual cut. The cut area varied between 127 and 1116 cm^2, corresponding to diameters between 12.7 and 37.7 centimetres. For all observations, the cutting time averaged 0.49 s; this is the cutting time for cutting slices that were approximately 27.5 centimetres in diameter (cut area ~600 cm^2).

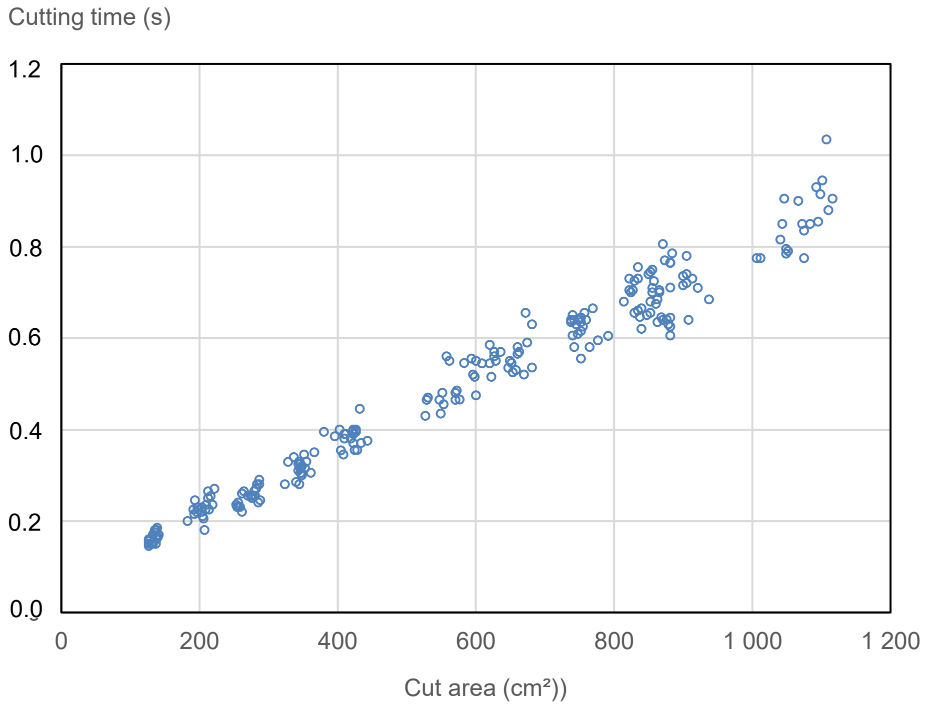

Figure 13.
Plot of the relationship between cut area and cutting time for all measurement values in the study.

The regression lines for the treatment relationship between cut area and cutting time are shown in Figure 14. For three of the treatments, evaluated with the new chains, Carlton B8, STIHL RMH and Oregon 18HX, the regression lines were almost identical. For the fourth chain model evaluated with new chains, STIHL RMHS, the regression line indicated a shorter cutting time at a given cut area, where the average difference was 6 percent. In Appendix 3 the treatment regression equations for the relationships between cut area and cutting time are shown, and in Appendix 4 and 5 the plots of the underlying measurement values by treatment are shown.

The regression lines for the treatment with the sharpened Carlton B8 chain indicated that this treatment had the shortest cutting time at a given cut area (Figure 14). To quantify the effect of sharpening, a comparison was made with the new Carlton B8 chain. The comparison showed that sharpening reduced cutting time by an average of 9 percent.

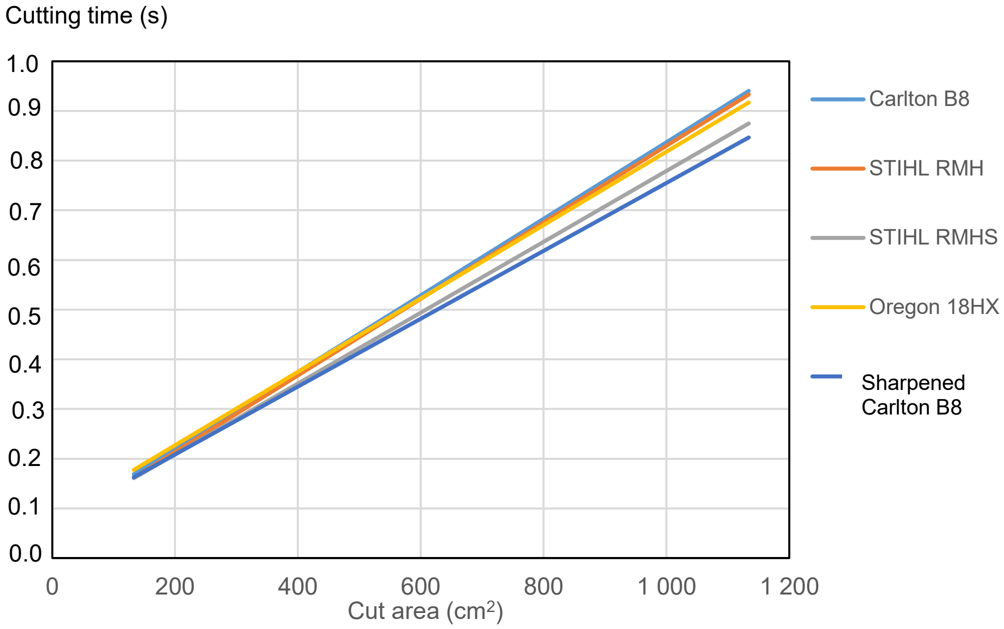

Figure 14.
Regression lines for the treatment relationship between cut area and cutting time.

Significance tests showed that the differences in cutting time between the STIHL RMHS and the other three chain models evaluated with new chains were statistically significant with a very high degree of certainty ($p < 0.0001$; Figure 15). In the same way, the differences in cutting time between the treatments with new and sharpened Carlton B8 chains were statistically significant with a very high degree of certainty ($p < 0.0001$).

In the study, we also investigated differences in average cutting time between chains within treatment (Figure 16). The effect of the individual chain was less certain, and was more subjected to variation linked to varying conditions in the wood in the individual cuts. However, for four of the treatments, there were small differences in average cutting time between the chains (average 1.6 percent). For the fifth treatment, with the new Carlton B8 chains, the difference was greater (3.9 percent). This difference was statistically significant with a low degree of certainty (p = 0.04). In the study, the chains in the same treatment came from different manufacturing batches. From this and the above results, we draw the conclusion that the variation in performance between the chains within treatment was small. We also conclude that the cutting was done on a sufficiently large number of slices per chain to determine that the effect of the individual chain could be determined with sufficient certainty.

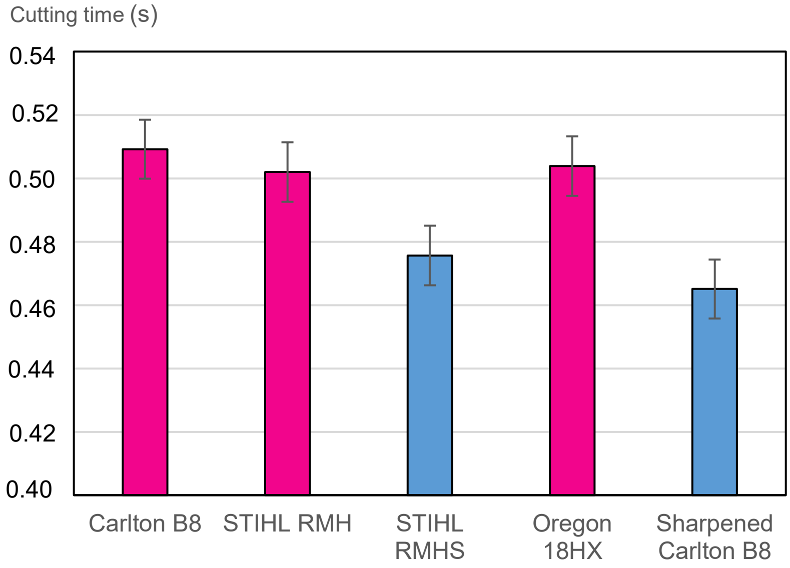

Figure 15.
Least square means with a 95 percent confidence interval for cutting time by treatment. The treatments with different colours are statistically separate, with a very high degree of certainty (p <0.0001). Note that the y-axis is truncated.

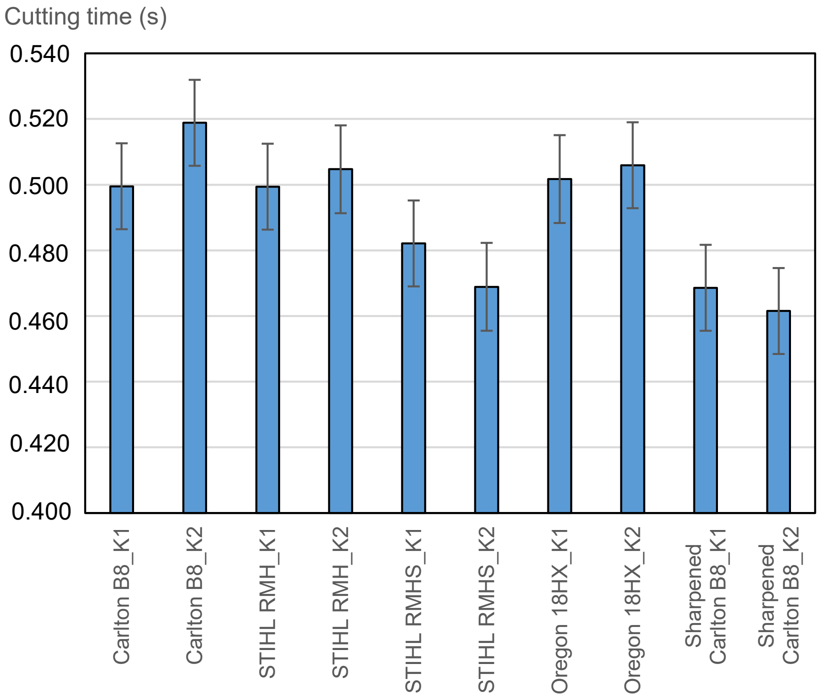

Figure 16.
Least square means with a 95 percent confidence interval for cutting time by treatment. Note that the y-axis is truncated.

The relationship between cut area and cutting time by treatment was used to investigate the cutting capacity of the saw chains (Figure 17). Generally, cutting capacity increased strongly with increasing cut area up to approximately 350 cm^2 cut area (diameter ~21 cm), after which the rate of increase slowed. Our interpretation is that the general increase in cutting capacity with increasing cut area is an effect of more cutting teeth being involved as the cut area increases. The differences that occurred between treatments for the relationship between cut area and cutting time were reflected in the relationship between cut area and cutting capacity. The Carlton B8, STIHL RMH and Oregon 18 HX had similar cutting capacity, while the cutting capacity for the STIHL RMHS and the sharpened Carlton B8 chain was higher over the studied diameter interval (Figure 17).

An interesting observation for the sharpened Carlton B8 chain was that the relative difference in cutting capacity in relation to the new Carlton B8 chain increased with increasing cut area (Figure 18). When the second chain with higher cutting capacity (STIHL RMHS) was compared with the new Carlton B8, the same tendency was not observed; here, the relative difference in cutting capacity was relatively constant apart from the smallest cut areas. This indicates that partly different mechanisms may be involved in causing the higher cutting capacity for the STIHL RMHS chain and the sharpened Carlton B8 chain. A detailed examination of these mechanisms is outside the scope of this study, but is an important area for future studies.

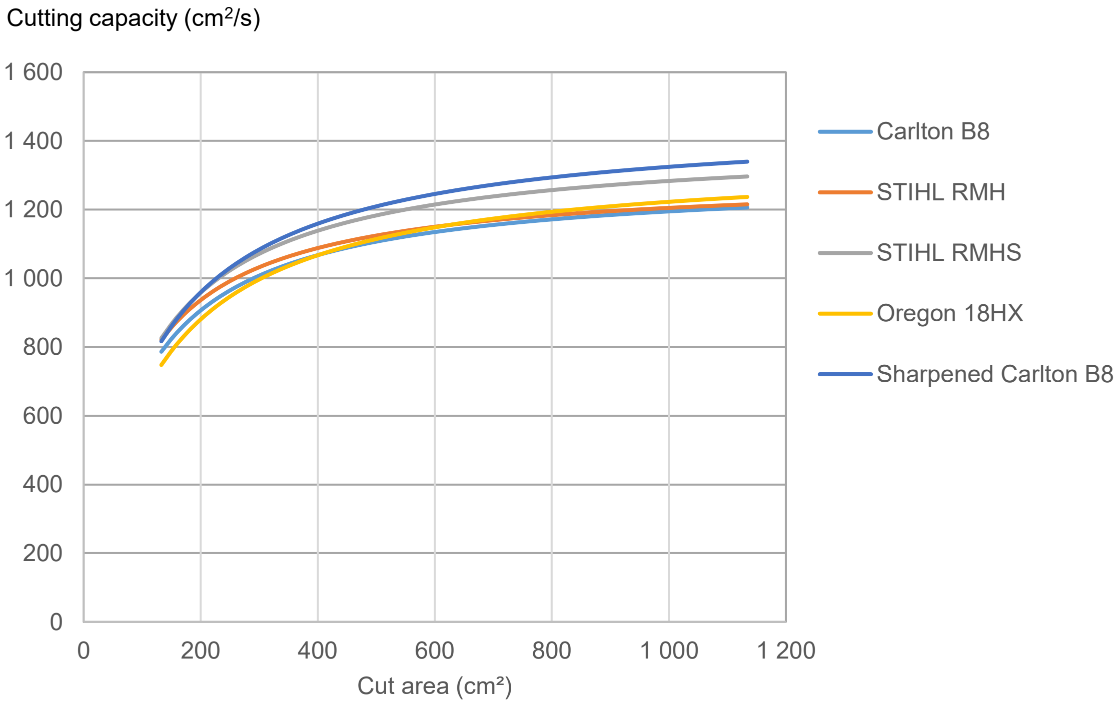

Figure 17.
Relationship between cut area and cutting capacity by treatment. Cutting capacity was calculated on using the relationship between cut area and cutting time by treatment.

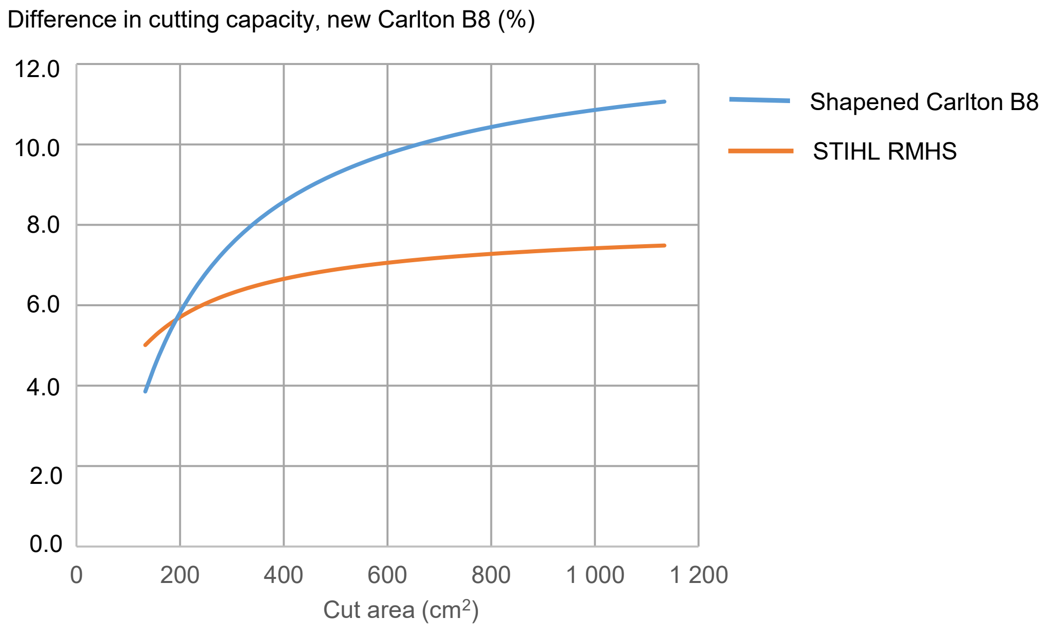

Figure 18.
Percentage difference in cutting capacity between the STIHL RMHS and the new Carlton B8 (orange line) respectively and between the sharpened Carlton B8 and the new Carlton B8 (blue line).

ENERGY CONSUMPTION

Energy consumption per cut was calculated by integrating the saw motor's instantaneous output power over cutting time, and where the instantaneous power was calculated from measurements of torque and revolutions during the cutting process (Equation 1). There was a tendency for the treatments with the highest cutting capacity (STIHL RMHS and sharpened Carlton B8) to have the highest average revolutions and lowest average torque (Table 4). However, the differences in relation to other treatments were small, and in no cases, were these differences statistically significant.

Table 4.
Least square means and 95 percent confidence interval for saw motor revolutions and torque in cutting, by treatment.

	Revolutions (rpm)			Torque (Nm)		
Treatment	**Mean**	**95 percent c.i. lower limit**	**95 percent c.i. upper limit**	**Mean**	**95 percent c.i. lower limit**	**95 percent c.i. upper limit**
Carlton B8	8 678	8 659	8 697	38.6	37.4	39.9
STIHL RMH	8 685	8 666	8 704	38.5	37.2	39.8
STIHL RMHS	8 705	8 686	8 724	38.2	36.9	39.5
Oregon 18HX	8 680	8 661	8 700	39.3	38.0	40.6
Sharpened Carlton B8	8 702	8 682	8 721	38.2	36.9	39.5

The lack of major differences in average motor speed and torque meant that differences between treatments in energy consumption largely reflected the differences between the treatments in terms of cutting time. Because the cutting time was shorter for the STIHL RMHS and the sharpened Carlton B8, the energy consumption was also less for these chains at a given cut area (Figure 19). Significance tests showed that the differences in average energy consumption between the STIHL RMHS and the other three chain models were statistically significant with a very high degree of certainty (p <0.0003; Figure 20). In the same way, the difference in average energy consumption between the treatments with new and sharpened Carlton B8 chains were statistically significant with a very high degree of certainty (p <0.0001).

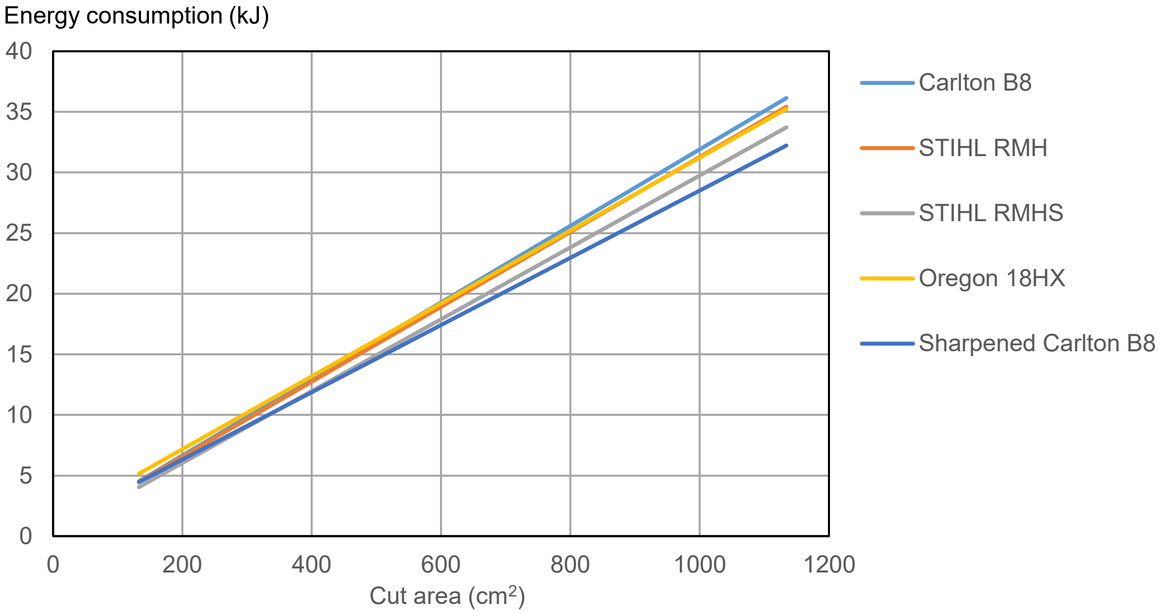

Figure 19.
Regression lines for the relationship between cut area and energy consumption by treatment.

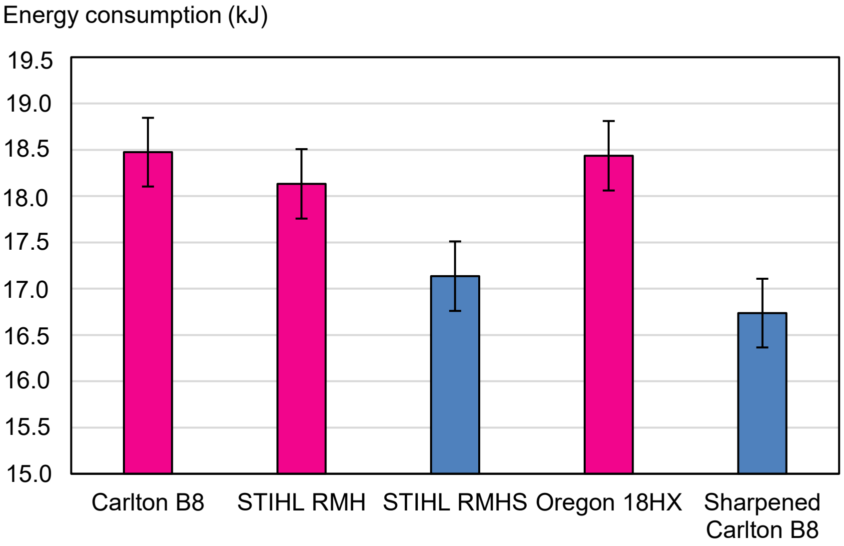

Figure 20.
Least square means with a 95 percent confidence interval for energy consumption by treatment in cutting. Treatments with different colours are statistically different, with a very high degree of certainty (p <0.0003). Note that the y-axis is truncated.

BAR FEED PRESSURE

The design of the saw motor used in the study (F11-iP) enables the speed to be held constant during the cutting process by using a constant flow valve that also indirectly controls the bar feed cylinder. Our study showed statistically significant differences between treatments for the average bar feed pressure during cutting (Figure 21). The biggest differences between the treatments were similar to the differences found for cutting time and energy consumption between, on the one hand, the STIHL RMHS and the sharpened Carlton B8 chain and, on the other, the Oregon 18 HX, STIHL RMH and the new Carlton B8 chain. While these treatment-based differences were observed, no statistically significant differences were found between treatments in terms of average torque and motor speed (Table 4). Our interpretation of the lower bar feed pressure at the same torque and speed for the STIHL RMHS and the sharpened Carlton B8 chain is that these chains cut more at a given bar feed pressure.

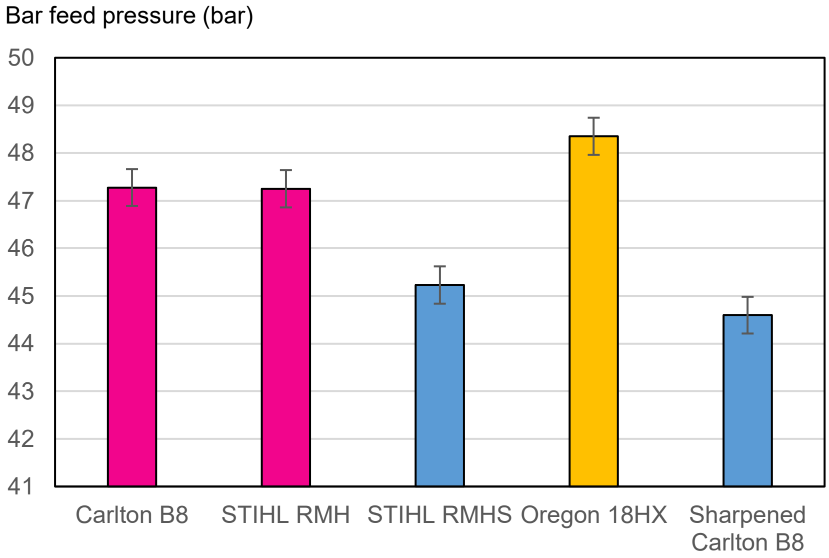

Figure 21.
Least square means with a 95 percent confidence interval for bar feed pressure by treatment in cutting. Treatments with different colours are statistically different, with a very high degree of certainty (p <0.0001). Note that the y-axis is truncated.

EXPLANATORY VARIABLES

Which mechanisms and underlying properties of the evaluated chains cause the differences observed in cutting time and energy consumption between treatments? A complete answer to this question lies beyond the scope of this study, but a detailed review of the results from the screening of sawdust samples gives certain clues.

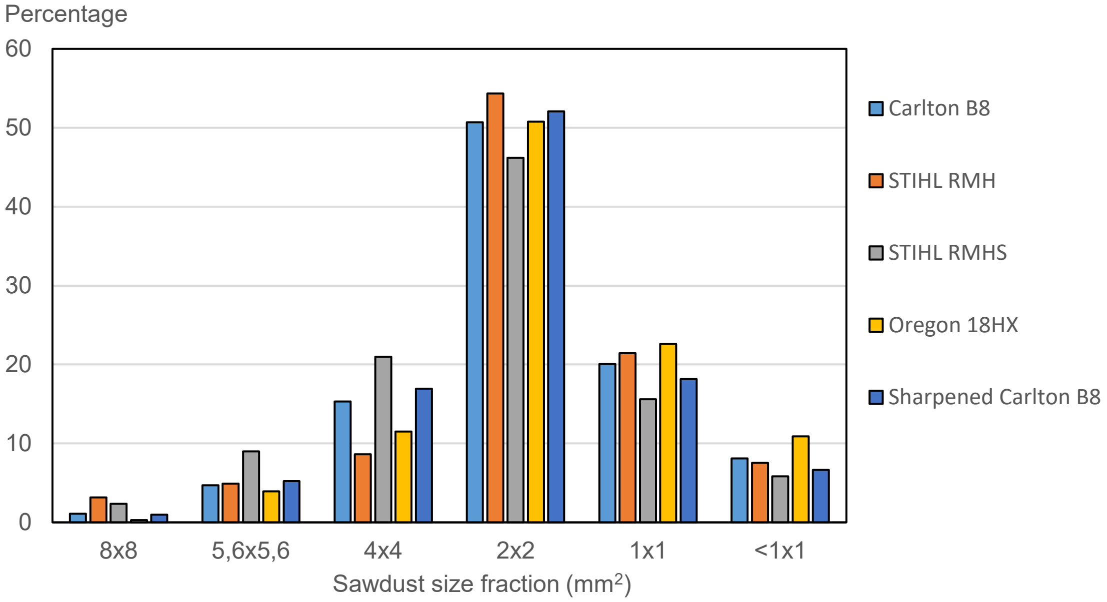

Figure 22.
Weight-based distribution of sawdust fractions for the evaluated chain models.

The composition of the sawdust fractions from the Carlton B8, STIHL RMH and Oregon 18HX chain models was similar, but the sawdust from the STIHL RMHS tended to comprise bigger fractions (Figure 22). The weight-based proportion of sawdust for the size fractions bigger than 4 mm^2 comprised 32 percent for this chain, while corresponding values for the other three chain models evaluated with new chains were 11 to 17 percentage points lower (Table 5).

In terms of geometric shape of cutting teeth, the STIHL RMHS differed from the other three chain models tested with new chains mainly because the area of the cutting teeth on this chain was 20 percent larger (Tabell 2). A possible explanation for the higher cutting capacity for the STIHL RMHS could be related to the larger cutting tooth area, which caused a higher average fraction size of sawdust and thereby more efficient cutting.

Another possible explanation for the greater cutting capacity of the STIHL RMHS is the lower cutting edge angle of the cutting teeth. Like the sharpened Carlton B8 chain, the STIHL RMHS had a 19-28 percent lower cutting edge angle than the other three chain models tested with new chains.

Table 5.
Weight-based proportion of sawdust with size fractions greater and smaller than 4 mm^2.

	Sawdust fraction	
Chain model	≥ 4 mm^2	< 4 mm^2
Carlton B8	21	79
STIHL RMH	17	83
STIHL RMHS	32	68
Oregon 18HX	16	84
Sharpened Carlton B8	23	77

The sharpened Carlton B8 chain had a higher filing angle and lower cutting edge angle than the new version (Table 3). Our conclusion was that it was the changed angles of the cutting teeth that lay behind the higher cutting capacity achieved with the sharpened chain. However, the sawdust size distribution was almost identical between the new and the sharpened Carlton B8 chain, i.e. our data does not support the idea that the more efficient cutting of the sharpened chain was achieved through a larger sawdust fraction size.

CONCLUDING DISCUSSION

Our study showed statistically significant differences in cutting time and energy consumption between the most commonly used chain models for harvester heads. The study also showed that sharpening has a favourable effect on the same parameters. The observed effects of chain model and sharpening are so great that they should have a considerable effect on productivity and fuel consumption when logging with a harvester. However, new studies are needed to examine effects on wear, for example if the natural blunting of the chain occurs at different rates for different chain models/sharpening.

The test rig, in combination with the method used, was effective in using measurements from a limited data set to detect differences between treatments. The test rig could therefore be a practical resource for more work on developing chains and sharpening methods that increase cutting capacity and/or reduce energy consumption in cutting.

Conclusions

- Of the new chains, the Carlton B8, STIHL RMH and Oregon 18HX had almost identical cutting time and energy consumption. The STIHL RMHS had shorter cutting time (~6 percent) and lower energy consumption (~7 percent) than the other three new chains. These differences were statistically significant with a very high degree of certainty.
- The sharpened Carlton B8 chain had shorter cutting time (~9 percent) and lower energy consumption (~10 percent) than the new Carlton B8 chain. These differences were statistically significant with a very high degree of certainty.
- The bar feed pressure in cutting was lower for the STIHL RMHS and the sharpened Carlton B8 chain than for the other three new chains. The difference was approximately 6 percent and was statistically significant with a high degree of certainty.

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Appendix 1

Definition of the angles measured on the cutting teeth

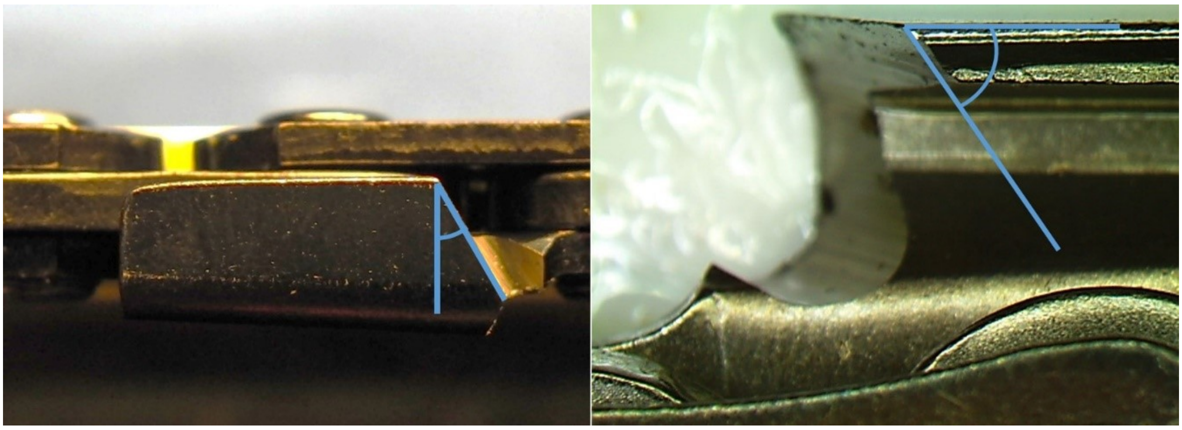
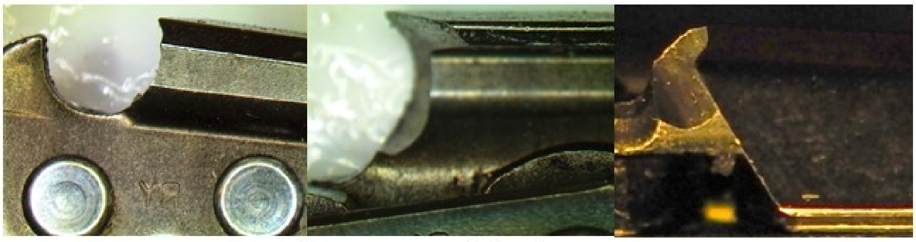


Figure 1.
Definition of filing angle (left) and cutting edge angle (right).

Appendix 2

Pictures of the cutting teeth on the evaluated chain models

Carlton B8

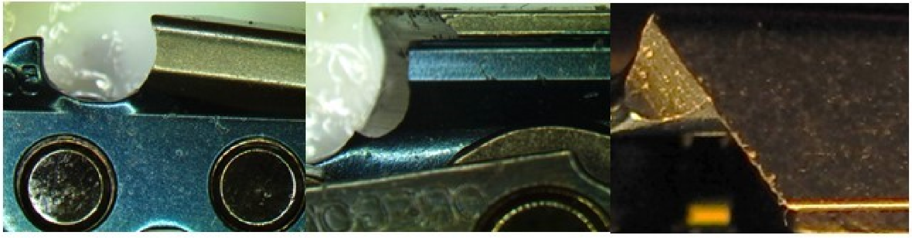


Carlton B8 Ljusdals sliptjänst

Stihl RMH

Stihl RMHS

Oregon 18HX



Appendix 3

Regression equations for the relationship between cut area and cutting time

Table
Regression lines for the relationship between cut area and cutting time, and the models' coefficient of determination.

Treatment	Regression equation[1)]	R^2
Carlton B8	Cutting time = 0.0665 + 0.00077 x cut area	0.98
STIHL RMH	Cutting time = 0.0595 + 0.00077 x cut area	0.99
STIHL RMHS	Cutting time = 0.0661 + 0.00071 x cut area	0.98
Oregon 18HX	Cutting time = 0.0795 + 0.00074 x cut area	0.98
Sharpened Carlton B8	Cutting time = 0.0719 + 0.00068 x cut area	0.98

[1)] Units for cut area and cutting time are cm^2 and seconds.

Appendix 4

Plots of cut area against cutting time for new chains

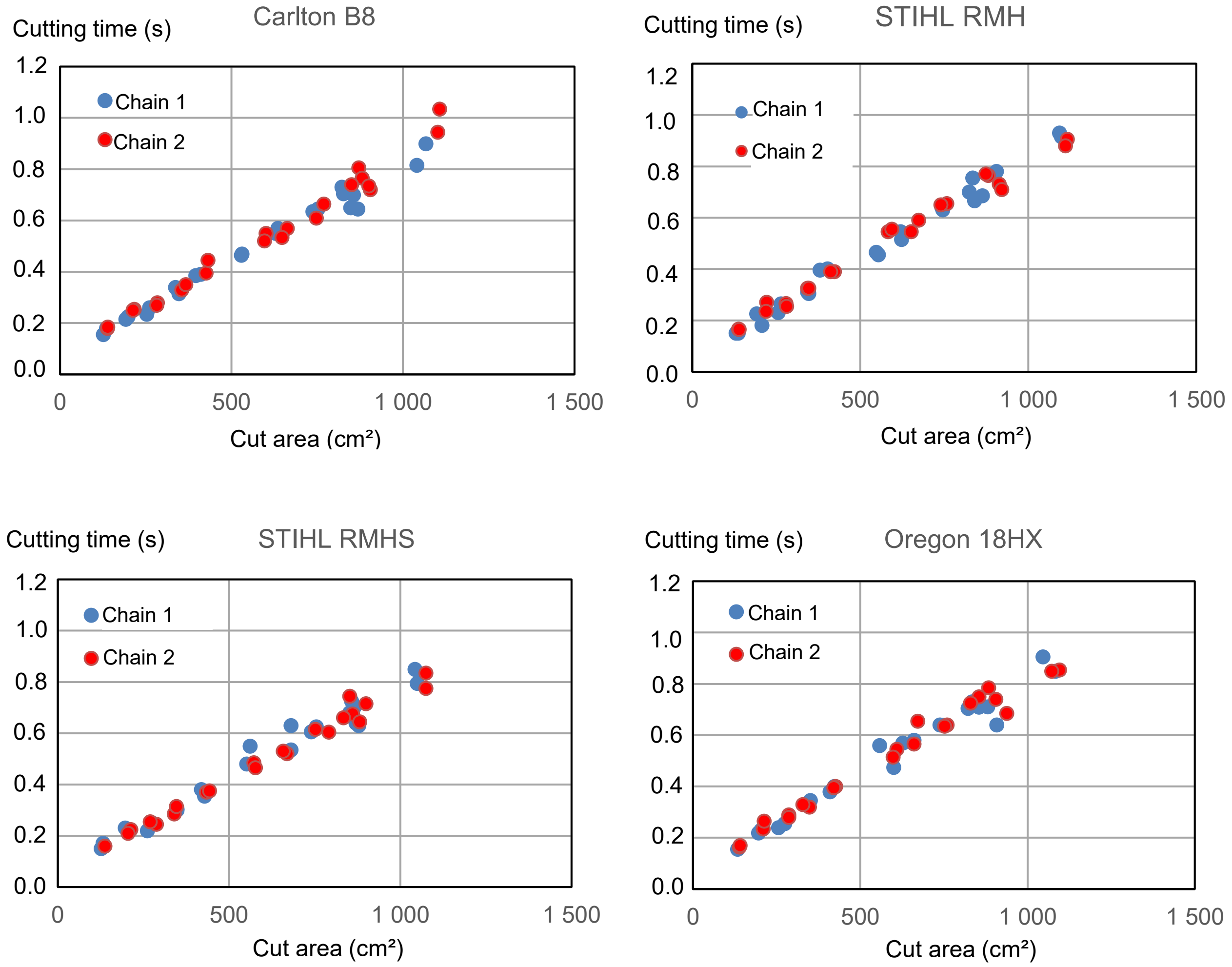


Figure 1.
Plots of cut area against cutting time (slices) for the four chain models evaluated with new chains. Each data point represents measurement values for a cut slice. Measurement values for the two chains within the chain model are marked with blue and red respectively.

Appendix 5

Plots of cut area against cutting time for sharpened chains

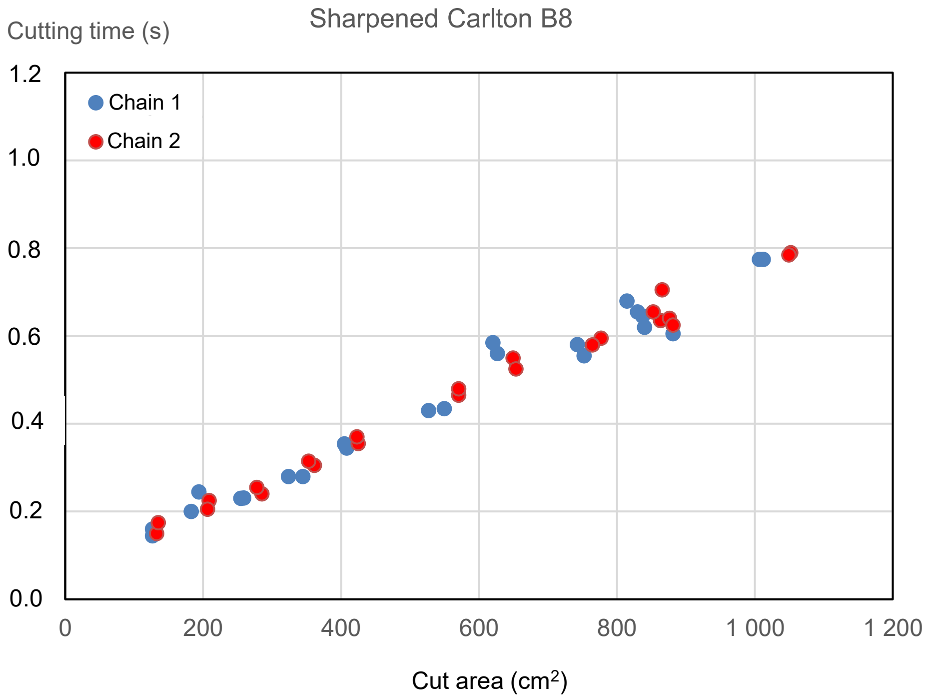


Figure 1.
Plots of cut area against cutting time (slices) for the sharpened chains. Each data point represents measurement values for a cut slice. Measurement values for the two chains within the chain model are marked with blue and red respectively.

Arbetsrapporter från Skogforsk fr.o.m. 2015

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