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Analysis of selected functional parameters of saw chains

Pavel Nevrkla, Luboš Staněk, Jindřich Neruda*

Department of Engineering, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

**Corresponding author: pavel.nevrkla@mendelu.cz*

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Abstract: Results obtained from the research study focused on the functional parameters of five saw chains tested on a test bench equipped with an electrically driven chain saw brought a number of findings. One of the most important of them is the significant difference between the cutting rates of round and square chains. The cutting rate of square chains R = 27.9 cm^2·s^{-1} is about 12% higher than the cutting rate of round chains. The influence of the chain construction on the chain cutting rate was conclusively demonstrated – the cutting rate of chains with a square profile is higher than the cutting rate of round-profile chains. It was further found out that although the specific energy E_m = 77.8 Ws·cm^{-2} is by ca. 7% lower in the square chain than in the round chain, Student's t-test did not reveal any statistically significant difference in the data on the specific energy consumption of round and square chains, i.e. the influence of the chain design on the specific energy consumption of the chain at cutting was not clearly demonstrated. Other findings, for example, showed that working with a loose saw chain on the guide bar impairs parameters of the chain operation or that energy demands of cutting with the saw chain are directly proportional to wood density (hardness) and increase with the decreasing wood moisture. Yet another finding was learning the energy flow structure, which indicated that 46% of total power input is consumed by the electric motor alone for its operation while only about 7% goes for driving the chain movement along the bar (without cutting) and power input required for cutting is approximately 46%.

Keywords: chainsaw; cutting rate; energy consumption; power saw; structural arrangement

The cutting (saw) chain is an endless cutting tool consisting of three types of links/cells (cutting, guiding and connecting), mutually coupled by rivets and circulating along the guide bar, being driven by the sprocket. It is probably the most widely used instrument for mechanised cutting of wood in the world and typically used in portable chainsaws. It is however also a part of working systems in harvesters as well as in some machines used in timber yards and sawmill operations. Working links of contemporary saw chains apply the principle of the chipper tooth which takes exactly determined thickness of chips that is delimited by a height difference between the back-cutting edge and the depth gauge. Compared to the formerly used scratcher-type chains, the benefits of the chipper-type chains are namely high cutting rate, capacity of cutting wood fibres in all directions and comfortable sharpening directly on the site (Neruda et al. 2022). The guide bar leads the saw chain into a desirable direction, maintaining it within the cutting plane (Kuvik et al. 2021). The absence of a strong kinematic bond between the system of cutting elements and the bar provides for a more rational path of the saw chain movement, which decreases the outline dimensions of the cutting mechanism in relation to the surface being cut (Kováč et al. 2013).

The principle of cutting wood with a saw chain is generally well known; however, the use of saw chains appears simple only at first glance. There

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is namely a range of parameters and factors in saw chains that affect their function. The fact that working links may deviate from the plane of the cut during the operation makes the process of cutting with the chain saw different from e.g. cutting with circular and band saws (Maciak et al. 2018). Cutting processes can be classified as continuous and discontinuous (Kaczmarek 1971). The angular speed of the engine shaft, chainsaw weight and number of teeth in the driving sprocket were found to significantly affect changes in the cutting resistance (Obliwin et al. 1988). Some researchers claim that high variability of the cutting force is caused by chain saw blades going through successive annual rings (Wyeth et al. 2009). Gendek (2005) informs that the frequency of changes in the chain saw cutting resistance corresponds to the motor working cycle. He concluded that inertial forces developing due to the combustion cycle affect the chain tension, thus changing the angle of cutting blades to the plane of the section, which shows in a variable immediate cutting force. An important parameter in wood cutting is the feed force used by the operator. According to Więsik (1994), the maximum feed force should not exceed the value that is necessary for obtaining shavings of thickness delimited by the depth gauge, as higher feed forces lead to a sharp increase in energy losses in the process of wood cutting.

The speed of saw chains ranges from 20 $m\cdot s^{-1}$ to 25 $m\cdot s^{-1}$, which allows for achieving higher cutting performance (Štollmann, Slugeň 2009). Chain speed and chip thickness are two important factors in the mechanics of cutting by chain. Changes in the chain speed and chip thickness may affect cutting forces and, hence, energy consumption and efficiency (Otto, Parmigiani 2015). Many researchers studied the influence of various factors on cutting performance as well as the influence of cutting machines on humans and their living environment (Sowa 1989; Stempski, Grodecki 1998; Wojtkowiak 2004).

In general, different cutting forces develop in orthogonal cutting of different types of wood of the same moisture and density (Koch 1964; Cristóvão et al. 2012). Heinzelmann et al. (2011) claim that losses due to friction in the cutting system of the chain saw increase with the increasing chain speed. Regression models based on experimental data show that cutting forces increase with the increasing thickness of chips (Reynolds et al. 1970). It was also found out that cutting speeds dramatically increase when depth gauges of chain saw cutting teeth are markedly lowered (Coutermarsh 1989). Extensive overviews on cutting force modelling at cutting wood were published by Marchal et al. (2009) and Wyeth et al. (2009). They pointed out that cutting forces closely relate to the choice of the tool material, its service life, quality of the treated surface, formation of chips, geometry of cutting tool blades and conditions of cutting.

Functional parameters of saw chains can be classified into several groups. The most basic parameters can be considered the following ones:

- design features of chains – material, shape and dimensions of cells and chains, geometry of blades;
- functional parameters – cutting capacity/cutting performance, energy consumption for cutting, rotational speed of chain, thickness of resulting chip;
- ergonomic parameters – noisiness of moving chain and vibrations caused thereby, environment contamination by jetted lubrication oil.

The goal of the research study, some results of which are presented in this paper, was to identify and compare functional parameters of several commonly used types of saw chains and to obtain more exact findings about their utility properties. There is a considerable amount of new findings, such as values of cutting rate and power input, parameters of the geometry of cutting cell blades, emissions of noise and vibrations, etc. Recorded data allow their analysis and searching for possible dependencies. As all findings cannot be presented in one paper, we present only several themes in this study: assessment of possible differences in cutting rate and energy consumption in dependence on the basic design of chain links (square and round profile), and identification of the partial energy consumption of power chain saw at cutting. This research study should either confirm or refute the traditional information that saw chains with a square profile have better cutting properties compared with saw chains with a round profile, and define the composition of energy flow characteristics for the motor and chain driving on the bar at cutting wood.

MATERIAL AND METHODS

A set of 5 saw chains (STIHL AG, Germany) was purchased for the research in the public shopping network. The set represented both design

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groups of saw chains whose parameters were the subject of interest of the research study, i.e. 2 chains with a round profile and 3 chains with a square profile. These types of chains were selected because they are commonly used in practice and are readily available in stores. The size of chains was identical: chain pitch 3/8', saw bar length 40 cm. Basic data on the tested saw chains are presented in Table 1.

Saw chains used in the research were in the original state from the manufacturer without any additional treatment by sharpening or depth gauge reduction (design schemes by STIHL AG).

The saw chains were tested using a test bench constructed by the authors for the research – see Figure 1. The Stihl E20 chainsaw (STIHL AG, Germany) with the mains power supply of 230 V was installed in the holder of the bench working mechanism and the tested chains were gradually fixed on its bar. The chainsaw used had accumulated more than 700 h of cutting time under operational conditions. The reason for using the chainsaw was the relatively easy and accurate reading of the immediate engine input value, which was needed for testing chains and measuring energy consumption at cutting. The saw power supply cable was connected to an electronic measuring system which allowed to measure the values of saw engine power consumption P (W) and to record their course as well as the time lengths of individual cuts. The electronic measuring system recorded power consumption at a frequency of 1 millisecond. The bench guaranteed constant conditions for test cutting both in terms of cut kinematics and cutting device feeding pressure (resolved by weight suspended on the bench revolving mechanism). The saw engine was automatically switched on and off by a system of limit switches. The switch went on as soon as the saw was released from being arrested in the basic position and began to cut, and it went off as soon as a test body was cut by the tested chain. This made it possible, among other things, to accurately record the times of individual cuts for the subsequent calculation of the cutting rate of chains R ($cm^2 \cdot s^{-1}$). The saw was attached to the support mechanism of the bench by means of four rubber-metal elements (silent blocks) dampening saw vibrations into the bench structure.

Wood samples. The chains were tested on several fresh samples of tree species – spruce (moisture 44%), larch (moisture 35%), oak (moisture 41%), and on two dry samples – pine (moisture 24%) and oak (moisture 25%). Each of the tested chains was used for test cuts of all wood samples. To minimise the blunting of chains

Table 1. Tested saw chains (design schemes by STIHL AG, Germany)

Serial No.	Model	Profile	Type	Depth gauge reduction (chip thickness)	Angle of sharpening according to manufacturer	Safety chain modification
1		round	Stihl 36 RM 60 Micro		30°	no
2		square	Stihl 36 RS 60 Super		30°	no
3		round/ semi-square	Stihl 36 RD3 60 Duro	0.65 mm	30°	yes
4		square	Stihl 36 RH 60 Hexa		25°	no
5		square	Stihl 36 RS3 60		30°	yes

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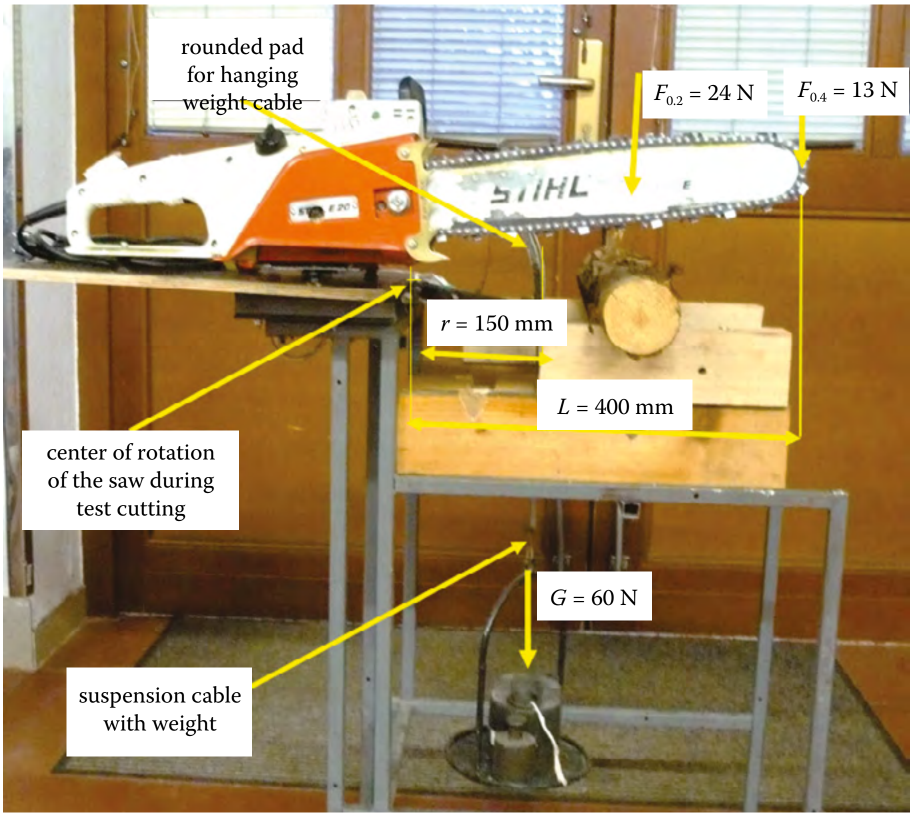

Figure 1. Test bench arrangement for testing saw chains

$F_{0.2}$ – pressing force measured at a distance of 0.2 m from the center of rotation; $F_{0.4}$ – pressing force measured at a distance of 0.4 m from the center of rotation; r – constant distance of the center of gravity of the pressing weight from the center of rotation; L – effective length of the guide bar; G – weight of the pressing load

by test cuts and to avoid their sharpening during the tests (and to introduce the human factor into measurements caused by imperfect sharpening), the number of test cuts was limited to two for each tree species. Test bodies were tree stems of 12–15 cm in diameter that were fixed in the test bench holder perpendicularly to the saw bar axis. After each cut, the diameters of the cut-off sections were measured crosswise, which allowed an accurate calculation of individual cutting faces and allocation of relevant times of cutting to them in order to define the cutting rate in $cm^2 \cdot s^{-1}$.

To identify partial energy consumption by individual components of the test electric chainsaw (saw engine alone, engine + drive of cutting part without cutting and overall input power at cutting), the part measuring the energy input was split into the following variants: (*i*) saw engine alone, (*ii*) saw with the fixed cutting part without cutting, (*iii*) saw performing the cutting.

The tested chains were installed on the saw bar at identical tension in such a way that the chain with optimum tension could be moved away from the bar edge in half the length of the bar up to half the height of the guiding link by pulling at a force of 20 N.

The share of saw chain tension in energy consumption was another studied parameter. Some measurements were therefore done with intentionally poorly tensioned (loosened) chains (due to gravitation, the chain in half the length of the bar was slack to half the height of the guiding link), which is a situation quite frequently occurring in operational practice.

The obtained data were processed into tables and diagrams, and some of them were subjected to basic statistical surveys for possible correlations.

RESULTS

Table 2 presents all main data recorded on the test bench (power inputs, cutting times, and diameters of cut-off wood discs) or calculated from them (size of cross-sectional areas, energy consumption for cutting the sample, specific energy consump-

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Table 2. Data for the statistical testing of differences in cutting rate and energy consumption between square and round tightened chains

No.	Species	ρ (%)	Chain	D_1 (mm)	D_2* (mm)	$\bar{D}$ (mm)	S (mm²)	S (cm²)	P (W)	t (0.01 s)	t (s)	E (Ws)	E_m (Ws·cm⁻²)	R_1, R_2 (cm²·s⁻¹)
10	spruce	44	chain 01 round profile, tightened	81	89	85.0	5 674	56.74	1 868	186.0	1.9	3 474	61.2	30.5
				87	88	87.5	6 013	60.13	1 875	186.0	1.9	3 488	58.0	32.3
12	larch	35		86	90	88.0	6 082	60.82	1 983	221.0	2.2	4 382	72.1	27.5
				85	92	88.5	6 151	61.51	1 864	209.0	2.1	3 896	63.3	29.4
14	oak	41		77	81	79.0	4 902	49.02	1 819	244.0	2.4	4 438	90.6	20.1
				76	78	77.0	4 656	46.56	1 830	266.0	2.7	4 868	104.5	17.5
16	pine	24		74	75	74.5	4 359	43.59	1 986	221.0	2.2	4 389	100.7	19.7
				86	93	89.5	6 291	62.91	1 952	221.0	2.2	4 314	68.6	28.5
18	oak	25		83	78	80.5	5 089	50.89	2 104	244.0	2.4	5 134	100.9	20.9
				83	82	82.5	5 345	53.45	2 096	232.0	2.3	4 863	91.0	23.0
20	spruce	44	chain 02 square profile, tightened	90	85	87.5	6 013	60.13	2 073	189.0	1.9	3 919	65.2	31.8
				80	85	82.5	5 345	53.45	2 005	200.0	2.0	4 010	75.0	26.7
22	larch	35		89	82	85.5	5 741	57.41	2 127	174.0	1.7	3 700	64.5	33.0
				84	88	86.0	5 809	58.09	2 155	174.0	1.7	3 750	64.6	33.4
24	oak	41		78	82	80.0	5 026	50.26	2 090	185.0	1.9	3 867	76.9	27.2
				79	84	81.5	5 217	52.17	2 090	185.0	1.9	3 867	74.1	28.2
26	pine	24		72	70	71.0	3 959	39.59	2 117	169.0	1.7	3 577	90.4	23.4
				75	72	73.5	4 243	42.43	2 123	170.0	1.7	3 610	85.1	25.0
28	oak	25		86	85	85.5	5 741	57.41	2 068	257.0	2.6	5 315	92.6	22.3
				84	82	83.0	5 410	54.10	2 140	193.0	1.9	4 130	76.3	28.0
30	spruce	44	chain 03 round profile, tightened	84	74	79.0	4 902	49.02	2 044	193.0	1.9	3 944	80.5	25.4
				86	83	84.5	5 608	56.08	1 808	207.0	2.1	3 743	66.7	27.1
32	larch	35		84	85	84.5	5 608	56.08	2 075	209.0	2.1	4 337	77.3	26.8
				87	87	87.0	5 945	59.45	2 078	239.0	2.4	4 965	83.5	24.9
34	oak	41		78	77	77.5	4 717	47.17	2 123	180.0	1.8	3 821	81.0	26.2
				79	79	79.0	4 902	49.02	2 163	180.0	1.8	3 894	79.4	27.2
36	pine	24		67	73	70.0	3 848	38.48	2 117	174.0	1.7	3 683	95.7	22.1
				71	70	70.5	3 904	39.04	2 117	174.0	1.7	3 683	94.4	22.4
38	oak	25		90	90	90.0	6 362	63.62	2 103	323.0	3.2	6 791	106.8	19.7
				87	88	87.5	6 013	60.13	2 105	282.0	2.8	5 936	98.7	21.3
40	spruce	44	chain 04 square profile, tightened	83	82	82.5	5 345	53.45	2 117	181.0	1.8	3 831	71.7	29.5
				85	83	84.0	5 542	55.42	2 030	204.0	2.0	4 141	74.7	27.2
42	larch	35		87	86	86.5	5 876	58.76	2 168	192.0	1.9	4 162	70.8	30.6
				89	82	85.5	5 741	57.41	2 153	192.0	1.9	4 133	72.0	29.9
44	oak	41		74	80	77.0	4 656	46.56	2 110	191.0	1.9	4 030	86.5	24.4
				84	78	81.0	5 153	51.53	2 103	191.0	1.9	4 017	78.0	27.0
46	pine	24		71	68	69.5	3 794	37.94	2 107	191.0	1.9	4 024	106.1	19.9
				70	69	69.5	3 794	37.94	2 123	176.0	1.8	3 737	98.5	21.6
48	oak	25		84	88	86.0	5 809	58.09	2 185	189.0	1.9	4 130	71.1	30.7
				82	91	86.5	5 876	58.76	2 155	189.0	1.9	4 073	69.3	31.1

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Table 2. To be continued

No.	Species	ρ (%)	Chain	D_1 (mm)	D_2* (mm)	$\bar{D}$ (mm)	S (mm²)	S (cm²)	P (W)	t (0.01 s)	t (s)	E (Ws)	E_m (Ws·cm⁻²)	R_1, R_2 (cm²·s⁻¹)
50	spruce	44	chain 05 square profile, tightened	84	81	82.5	5 345	53.45	1 972	188.0	1.9	3 706	69.3	28.4
				83	82	82.5	5 345	53.45	2 050	167.0	1.7	3 424	64.0	32.0
52	larch	35		82	88	85.0	5 674	56.74	2 053	186.0	1.9	3 818	67.3	30.5
				82	87	84.5	5 608	56.08	2 050	193.0	1.9	3 957	70.6	29.1
54	oak	41		84	77	80.5	5 089	50.89	2 110	187.0	1.9	3 946	77.5	27.2
				86	77	81.5	5 217	52.17	2 080	187.0	1.9	3 890	74.6	27.9
56	pine	24		69	65	67.0	3 526	35.26	1 949	181.0	1.8	3 527	100.0	19.5
				66	65	65.5	3 369	33.69	1 891	174.0	1.7	3 291	97.7	19.4
58	oak	25		81	92	86.5	5 876	58.76	2 183	207.0	2.1	4 518	76.9	28.4
				81	94	87.5	6 013	60.13	2 105	207.0	2.1	4 357	72.5	29.0

*mean cross-sectional areas D measured 'crosswise'; No. – serial number of measurement; ρ – moisture; chain – chain type and condition; D_1 – first measurement of sample diameter; D_2 – second measurement of sample diameter; $\bar{D}$ – arithmetic mean from two measurements $(D_1 + D_2)/2$; S – cross-sectional area; P – average power input at cutting the sample; t – time length of sample cutting; E – energy consumption for sample cutting; E_m – specific energy consumption; R_1, R_2 – cutting rates

Each measurement always included two cuts; therefore, individual measurements are recorded in two lines

tion and cutting rate/capacity). It also presents the tree species with the above-mentioned indicators and identification of tested chains as well as their tension (tight, slack). Studying the data in Table 2 (namely the 'converted' ones, i.e. specific energy consumption E_m (Ws·cm^{-2}) and cutting rate R_1, R_2 (cm^2·s^{-1}), differences apparently exist between the individual tested chains, which can be observed also in one chain in connection with cutting the wood of different tree species.

The differences are more apparent in Tables 3 and 4, which demonstrate the processing of data on specific energy consumption and cutting rate for chain 01 (Table 3) with the round profile and

Table 3. Changes in the values of specific energy consumption E_m and cutting rate $\bar{R}$ on an example of chain 01 (round profile)

Serial No. of measurement	Tree species	Moisture ρ (%)	Chain type and state at measurement	Specific energy consumption E_m (Ws·cm⁻²)	Average cutting rate $\bar{R} = (R_1 + R_2)/2$ (cm²·s⁻¹)
10	spruce	44	chain 01, tight	59.6	31.4
11	spruce	44	chain 01, slack	61.3	28.4
12	larch	35	chain 01, tight	67.7	28.5
13	larch	35	chain 01, slack	74.4	26.0
14	oak	41	chain 01, tight	97.4	18.8
15	larch	35	chain 01, slack	79.7	23.3
16	pine	24	chain 01, tight	81.7	24.1
17	pine	24	chain 01, slack	102.2	20.3
18	oak	25	chain 01, tight	95.8	21.9
19	oak	25	chain 01, slack	91.5	21.5
Chain 01, tight			arithmetic mean	80.4	24.9
			standard deviation	15.0	4.5
Chain 01, slack			arithmetic mean	81.8	23.9
			standard deviation	14.1	3.0

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Table 4. Changes in the values of specific energy consumption E_m and cutting rate $\bar{R}$ on the example of hain 02 (square profile)

Serial No. of measurement	Tree species	Moisture ρ (%)	Chain type and state at measurement	Specific energy consumption E_m (Ws·cm^{-2})	Average cutting rate $\bar{R} = (R_1 + R_2)/2$ (cm^2·s^{-1})
20	spruce	44	chain 02, tight	69.8	29.3
21	spruce	44	chain 02, slack	70.6	28.6
22	larch	35	chain 02, tight	64.5	33.2
23	larch	35	chain 02, slack	68.2	30.6
24	oak	41	chain 02, tight	75.5	27.7
25	larch	35	chain 02, slack	76.2	27.5
26	pine	24	chain 02, tight	87.6	24.2
27	pine	24	chain 02, slack	88.1	23.6
28	oak	25	chain 02, tight	84.7	25.2
29	oak	25	chain 02, slack	111.5	17.6
Chain 02, tight			arithmetic mean	76.4	27.9
			standard deviation	8.7	3.2
Chain 02, slack			arithmetic mean	82.9	25.6
			standard deviation	15.9	4.6

chain 02 (Table 4) with the square profile. It can be derived from Table 3 and Table 4, among other things, that:

– tree species/wood hardness affects both the specific energy consumption and the cutting rate;
– reduced wood moisture content increases the specific energy consumption and decreases the cutting rate;
– slack chain increases the specific energy of cutting and decreases the cutting rate;
– relatively large standard deviations between the respective chains indicate a significant variability of specific energy consumption and cutting rate in dependence on tree species and chain tightness;
– chain design affects both the specific energy consumption and the cutting rate, with round profile chains exhibiting higher specific energy consumption and lower cutting rate as compared with square profile chains (further details below).

Table 5 and Figure 2 present values of specific energy consumption and cutting rate for all tested chain types, at all times for properly tightened chains and slack (loosened) chains, the data being

Table 5. Values of specific energy consumption E_m and cutting rate $\bar{R}$ for all chains (tight and slack) and all tree species

Chain type and state at measurement	Specific energy consumption E_m (Ws·cm^{-2})		Average cutting rate $\bar{R} = (R_1 + R_2)/2$ (cm^2·s^{-1})	
	arithmetic mean	standard deviation	arithmetic mean	standard deviation
Chain 01, tight	80.4	15.0	24.9	4.5
Chain 01, slack	81.8	14.1	23.9	3.0
Chain 02, tight	76.4	8.7	27.9	3.2
Chain 02, slack	82.9	15.9	25.6	4.6
Chain 03, tight	86.3	10.9	24.3	2.5
Chain 03, slack	89.7	9.8	23.0	2.5
Chain 04, tight	79.8	12.0	27.2	3.7
Chain 04, slack	78.1	11.0	27.3	3.4
Chain 05, tight	77.0	11.5	27.1	4.0
Chain 05, slack	80.5	13.8	25.1	3.9

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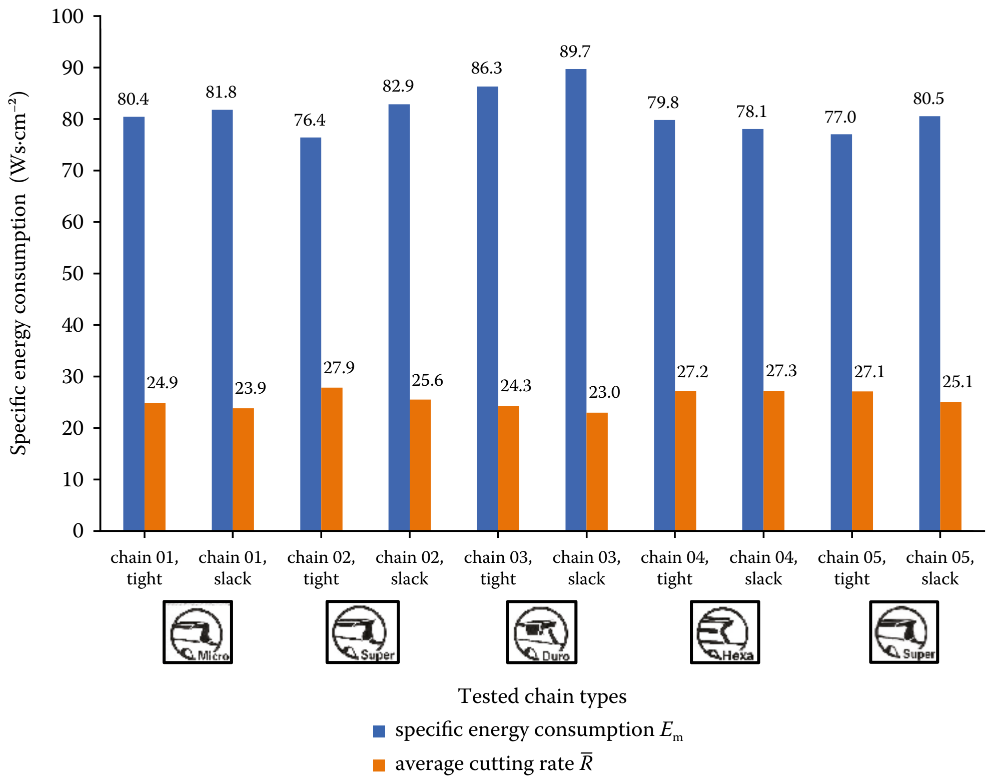

Figure 2. Average values of specific energy consumption E_m (Ws·cm^{-2}) and cutting rate $\bar{R}$ (cm^2·s^{-1}) for all tree species (design schemes by STIHL AG)

arithmetic means of all tree species used for test cuts. It can be derived from Table 5 and from the diagram in Figure 2 that:

– the specific energy consumption for all chains averages approximately 80 Ws·cm^{-2}, and the cutting rate ranges from 22 cm^2·s^{-1} to 30 cm^2·s^{-1};
– even the average values of specific energy consumption and cutting rate for all tree species exhibit differences in favour of square profile chains;
– even at this wide averaging, the insufficient tension of chains shows in the worsening of both the specific energy consumption and the cutting rate.

Table 6 and the diagram in Figure 3 provide interesting data as they bring partial values of energy demands of the energy chain: (*i*) engine, (*ii*) drive of the chain alone, and (*iii*) energy consumed by cutting. The table contains so-called cumulative power inputs which are engine power inputs starting with the engine alone, which will increase by energy for driving the attached cutting mechanism (moving without cutting), and the highest power input will occur at cutting the wood samples. The power input of the engine alone, recorded by measuring with the dismantled cutting device, is 1 008 W and is identical (constant) for all measurements. The partial power consumptions (the drive of the chain along the bar without cutting and the energy consumed for the actual cutting) are determined by subtracting the cumulative power consumptions from each other.

Table 6 shows that cumulative power inputs of the engine + cutting device are very similar in all tested chains and that pronounced differences in energy consumption come only in connection with the cutting itself. Percentages of partial power inputs are presented in the last column of Table 6. In all cases, the engine alone takes ca. 50% of the overall input at cutting, the drive of the chain along the bar (without cutting) nearly always only 7% of the overall input at cutting, and the second most significant consumer of power input is the cutting itself (50% of the overall input at cutting). The facts are graphically represented in Figure 3 showing energy relations in the wide average of all chains and tree species.

Above, it was stated several times that the cutting rate values differ between the respective chain types in favour of chains with square profiles. Differences in the values of specific energy consumption are also mentioned, although

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Table 6. A structured overview of partial power inputs in tested chains

Tested chain/profile	Situation at measuring cumulative input	Cumulative inputs (W)	Partial inputs (W)	Partial inputs (%)
Chain 01, round	engine alone (bar with chain not attached)	1 008	1 008	52
	running chain (without cutting)	1 143	135	7
	cutting	1 938	795	41
Chain 02, square	engine alone (bar with chain not attached)	1 008	1 008	48
	running chain (without cutting)	1 143	135	6
	cutting	2 099	956	46
Chain 03, round	engine alone (bar with chain not attached)	1 008	1 008	49
	running chain (without cutting)	1 143	135	7
	cutting	2 063	920	45
Chain 04, square	engine alone (bar with chain not attached)	1 008	1 008	47
	running chain (without cutting)	1 143	135	6
	cutting	2 135	992	46
Chain 05, square	engine alone (bar with chain not attached)	1 008	1 008	49
	running chain (without cutting)	1 143	135	7
	cutting	2 044	901	44
All chains	engine alone (bar with chain not attached)	1 008	1 008	47
	running chain (without cutting)	1 165	157	7
	cutting	2 166	1 001	46

Table 6 brings averages of cumulative and partial power inputs always for all tree species

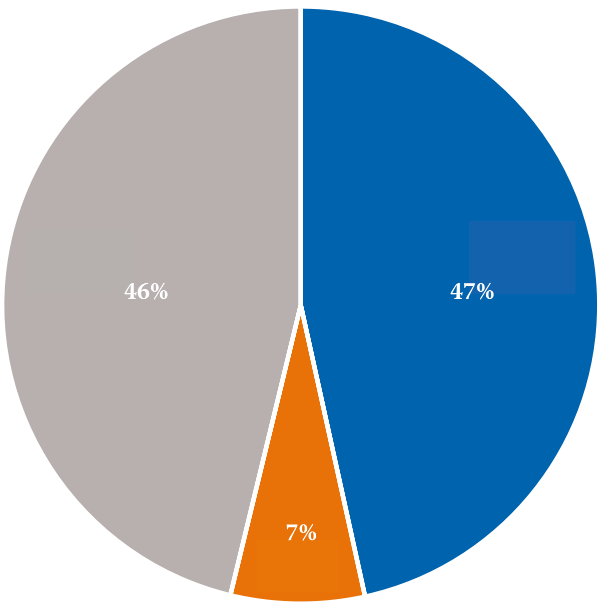

Figure 3. Summary structure of chainsaw inputs (for all chains and all tree species, chains tight)

the findings are not as clear as in the variable of the cutting rate.

To be able to make an informed and responsible decision about the real existence of the above-mentioned differences in the cutting rate and specific energy consumption and avoid their being a mere assumption stemming from the visual comparison of tabular data, a basic statistical analysis was performed for the two variables. The results of the analysis are presented in Table 7. Regarding the fact that the number of individual measurements was not too high (see explanation in the Material and Methods above), the significance of differences in the values of cutting rate and specific energy consumption of cutting was tested using the principle of small frequency sample means. When the range of files is small, principles for assessing them with the normal distribution of frequencies cannot be used. In our case, we chose the so-called Student's *t*-test which evaluates the similarity of two files using the so-called Student's *t*-number. 'Degrees of freedom' are introduced, which are determined according to the formula ($n_1 + n_2 - 2$), where n_1 and n_2 are the frequencies of one and the other compared file. This *t*-number

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Table 7. Testing the influence of chain design (round and square chains) on its cutting rate and specific energy consumption

Parameter	Unit	Method of evaluation	Decisive quantity	Degrees of freedom n	Calculated value of decisive quantity t	Critical value of decisive quantity $t_{0.025}$	Relation between the calculated and critical values of decisive quantity	Result
Cutting rate	$cm^2 \cdot s^{-1}$	Student's t-test	Student's number t	48	2.307	2.01	t (2.307) > $t_{0.025}$ (2.01)	Statistically significant difference between the data on the cutting rate of round and square chains; the influence of chain design on its cutting rate was clearly demonstrated.
Specific energy consumption	$Ws \cdot cm^{-2}$	Student's t-test	Student's number t	48	1.711	2.01	t (1.7117) < $t_{0.025}$ (2.01)	Statistically non-significant difference between the data on the size of specific energy at cutting by round and square chains; the influence of chain design on its energy demand was not demonstrated.

value is calculated for the given files and is compared with the tabular critical t-number value for the calculated number of degrees of freedom and 1% or 5% level of significance. Two essential facts following out from Table 7 are as follows:

– There is a statistically significant difference between the data on the cutting rate of round and square chains. The influence of the chain design on its cutting rate was clearly demonstrated. The cutting rate of square-profile chains is higher than the cutting rate of round-profile chains.
– There is no statistically significant difference between the data on the specific energy consumption of round and square chains. The influence of the chain design on its specific energy consumption was not clearly demonstrated. The specific energy consumption of square-profile chains thus does not significantly differ from the specific energy consumption of round-profile chains.

DISCUSSION

The research study, which tested different saw chain designs, produced some important findings that can be compared with those of other authors.

The basic parameters of the cutting mechanism are chain type and dimensions, which determine the dimensions and construction of its other parts. Another important parameter is the tooth pitch, which is half the distance between three consecutive rivets of the chain (Mikleš et al. 2011). Therefore, we used saw chains of identical size in our research study because otherwise, the results would be incommensurable.

Engine performance has a significant influence on the efficiency of cutting, its increase resulting in the growing power input of cutting device and hence usable feed force and chip thickness. Nevertheless, the feed force, which directly relates to the pressure on the cutting device, must not be too high as that would lead to a sudden growth of chip thickness and cutting resistance. If the chain saw operator applies a too high feed force, the driving system overload may occur (Maciak 2001). This finding was accepted in the methodology of research when the feed force of the saw bar into cut was constant, secured by weight on the test bench, thus not being affected by the human factor.

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The main finding is apparently the fact that the construction of cutting teeth in saw chains was demonstrated to have a significant influence on the productivity of the process of cutting wood by the saw chain. There is a statistically significant difference between cutting rates of round and square chains. The cutting rate of square chains R = 27.9 $cm^2 \cdot s^{-1}$ is about 12% higher than the cutting rate of round chains. The effect of the chain design on its cutting rate was clearly demonstrated – the cutting rate of square-profile chains is higher than the cutting rate of round-profile chains.

The results of our study confirmed the initial assumption that saw chains with square-profile cutting teeth, sometimes referred to as chisel-type teeth, achieve higher cutting rates as compared with round-profile teeth. It can be stated that the higher cutting rate of square chains showed in all cut tree species. These findings correspond with results published by other authors. According to Kozłowski (2003), chains with round-profile teeth exhibit better performance in woody species with low density. On the contrary, chisel teeth exhibit higher cutting performance at cutting hardwoods of high density. Kozłowski (2003) claims, however, that chisel-type chain cells (in spite of reaching high efficiency) feature lower service life than semi-chisel cells.

When using a combustion engine saw, Gendek (2005) demonstrated the sameness in the frequency of cutting resistance changes with the engine working cycle. He found out that inertial forces following out from the working cycle of the engine cause a temporary shift of its voltage and hence the position of cutting teeth towards wood and differentiation of instantaneous cutting forces. An important parameter in cutting wood is the feed force applied by the chainsaw operator. Researchers agree that the value significantly determines the achieved cutting performance and its increase results in an increased performance level. Maciak (2001) informs that when the feed force is exceeded, the cutting performance is impaired. Cutting forces grow with the increasing wood density and decrease with the moisture content up to the point of fibre saturation (Koch 1964).

Cutting efficiency and energy consumption of chain saws are affected by the chain type, its tightening (Dąbrowski et al. 2012), wood density, i.e. tree species, moisture content (Otto, Parmigiani 2015; Kuvik et al. 2017) and namely by chain sharpness (Maciak et al. 2017). Despite the development of chain saws, there are still some phenomena decreasing their cutting performance (cutting rate). The main of them is the blunting of chains during the cutting of wood. It is a phenomenon closely related to wood cutting and even the latest solutions of cutting cell geometry are not able to eliminate it (Maciak et al. 2017). Blunting of the blades of saw chain cutting cells was not a subject of our research study as explained in the introduction; the mentioned finding can be naturally agreed with. Maciak (2015a) claims that the average cutting rate of cross-cutting using power chain saws is 29.1 $cm^2 \cdot s^{-1}$. The value matches our findings from the research study.

We also found out in our study that although the average value of specific energy E_m = 77.8 $Ws \cdot cm^{-2}$ is about 7% lower in the square chain than in the round chain, Student's t-test did not show any statistically significant difference between the data on the specific energy consumption of round and square chains. The influence of the chain design on its specific energy consumption at cutting was thus not clearly demonstrated. The reduction of specific energy of cutting by square chains is then rather insignificant compared with cutting by round chains.

The results of our study basically correspond with the results of other authors regarding variable energy demands for cutting wood by saw chains. This concerns, for example, higher energy requirements for cutting high density wood (hardwood). There is an assumption that higher cutting force is needed at higher wood density (softwood × hardwood) (Otto, Parmigiani 2015).

Our results also suggest that the tension of chains affects energy consumption; the effect is, however, not too significant. Similarly, Poje and Mihelič (2020) state that chain tension has only an insignificant influence on work efficiency and energy consumption.

The energy required to overcome the friction between the chain and the saw bar is low compared with the energy required for cutting wood (Poje, Mihelič 2020). This fact is also in line with our findings. Botwin and Botwin (1979) found out, however, that the slack saw chain is reducing cutting efficiency. Nevertheless, too high chain tension causes a considerable loss of energy by friction and earlier wear of the cutting device (Maciak, Kubuśka 2018). Moreover, efficiency worsens when

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the saw chain is tightened insufficiently (too loose) while the excessive chain tightness leads to high energy losses (friction) and increased wear of chains (Maciak 2013). Excessive tightness leads to considerable energy losses due to friction and faster wear of the cutting mechanism. Trzeciak (2003) confirmed in his research that the excessive tension of the saw chain results in the visibly decreased efficiency of cutting. Górski (1996) claims that the efficiency of cutting with the slack saw chain is even 50% lower compared with the correctly tightened chain. However, we did not arrive at the finding of such a high reduction in cutting rate due to the loose chain in our research.

In our research, differences were detected in cutting rate R ($cm^2 \cdot s^{-1}$) not only in dependence on the tree species but also on its moisture content. A significant difference namely exists between the cutting rate of fresh wood with high moisture and dry wood. This knowledge agrees with the published results of other authors. Maciak (2015b), for example, used pine samples of absolute moisture of 9.7% and 12.9%. Moisture and density can be in correlation with mechanical properties (Kretschmann 2010). Chuchala et al. (2014) explain cutting force changes in dependence on density at two different depths of the cut (thicknesses of chips).

Our results also confirmed the fact presented by Maciak (2007) that the efficiency of cutting wood by chain saw is, among other things, affected by many factors connected with the construction of cutting teeth (e.g. by cell type), their condition and direction of cutting towards the wood surface. To achieve high cutting performance, the saw chain must be properly tightened, the cutting blades should have proper angles, and their cutting edges have to be in good condition (Maciak 2001).

CONCLUSION

Results obtained from the research study focused on the functional parameters of five saw chains tested on a test bench equipped with an electrically driven power chainsaw brought a number of findings. One of the most important of them is the knowledge that there is a statistically significant difference between the cutting rates of round and square chains. The cutting rate of square chains $R = 27.9\ cm^2 \cdot s^{-1}$ is about 12% higher than the cutting rate of round chains. The effect of the chain design on its cutting rate was clearly demonstrated – the cutting rate of square-profile chains is higher than the cutting rate of round chains.

It was further found out that although the average value of specific energy $E_m = 77.8\ Ws \cdot cm^{-2}$ is about 7% lower in the square chain than in the round chain, Student's t-test did not show any statistically significant difference in the data on the specific energy consumption of round and square chains. Thus, the effect of the chain design on its specific energy consumption at cutting was not clearly demonstrated and is, therefore, little significant.

Other findings from our research study included, for example, the fact that working with the slack saw chain worsens the chain work parameters, that energy demands for cutting with the saw chain are directly proportional to wood density (hardness) and are increasing with the decreasing wood moisture content.

Yet another finding was the knowledge of energy flow structure where 47% of overall power input is consumed by the electric motor alone for its operation while driving the chain movement along the bar (without cutting) consumes only ca. 7% and the power input required for cutting is also approximately 46%.

Further research in this area could focus on comparing the performance of individual saw chains after one hour of cutting. This approach would provide valuable insights into practical applications and enhance the understanding of chain efficiency during extended use. Additional studies could also compare the efficiency of old and new chainsaws and cutting chains, as well as chainsaws of various types.

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