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THE EFFECT OF LOG SORTING STRATEGY ON THE FORECASTED LUMBER VALUE AFTER SAWING PINE WOOD

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ABSTRACT

The optimal transformation path for the resource is determined by the quality of a log combined with its dimension. The commercial value of derived products is also closely connected with the size and extent of containing wood deficiencies. The results of studies with three diverse strategies for log sorting are presented in the paper. Resource assessment by a worker without extensive experience in sorting logs, the certified grading expert, and the automatic in-line system including optical scanner with dedicated software are compared. It was shown that the lack of experience of the person performing the sorting operation results in reducing the potential economic profits of a sawmill. On the contrary, the overall efficiency of the log conversion process is considerably improved by the automated sorting systems with scanners. Early identification of logs optimal for specific lumber production is assured by reducing the human errors and subjective evaluation. Both, the yield of produced timber and profits of the sawmill are directly affected this way. It was demonstrated that the log sorting rate performed by the scanner is four times higher in comparison to grading by the certified expert, as well as three times higher compared to employee with no experience. The finding that the volume of high-quality lumber of elevated value is the lowest in the case the log is sorted by a human was proved.

Key words: pine, log sorting method, log quality, shape scanner, sawmill.

INTRODUCTION

A rise in demand for sawn timber in Poland has been noticed recently as a boost use of construction timber and expansion in the furniture manufacturing. Unfortunately, an increase in demand is not combined with the sufficient increase in log supply. High quality timber is used not only for high-value furniture and single-family houses but also for multi-story buildings, including both rafter framing (traditional and prefabricated) and cross-laminated timber structures (GOTYCH *et al*. 2009, KRZOSEK 2011). The shortage of supply and refined technical requirements for the construction material determine need for rationalization of the log use and consequent optimization of supply chains.

The quality sorting is relatively well developed routine for the output stream of the sawmill production, including grading diverse assortments of sawn timber. The visual assessment is still most widely implemented sorting method, especially in a small and medium size sawmills (WIERUSZEWSKI *et al*. 2019). However, fully automatic quality sorting systems become standard in high throughput mills due to limitations of the human-based assessment (SANDAK 2009). The quality aspects evaluated in such automatic systems include diverse material properties, such as dimensions, grain/fibre direction, mechanical properties, presence of wood defects, colour pattern density among the others. Specific technical solutions differs between scanner and include mechanical testing (KRZOSEK 2011), stress wave velocity/attenuation, as well as radiometric absorbance/reflectance /transmittance in different ranges of electromagnetic spectrum among the others (KROHN and PALM 1981, KOLB and GRUBER 1981, GÖRGÜN and DÜNDAR 2018, SANDAK and SANDAK 2017).

Even if sorting of timber is essential for assuring expected product quality and maximizing profits, the overall efficiency of the sawmill production can be substantially improved by appropriate sorting of logs and following optimization of the sawing pattern. The basic approach for quantifying log quality is a manual method described in standards, such as PN-92/D-95017 or EN1927-2:2008. In this case, an expert person performs set of manual measurements of the log geometry and identify presence of selected wood deficiencies noticeable on the log surface. It is clear that the correctness and repeatability of the grading decision, as well as time necessary for scrutinizing assessment will depend on the level of the operator training and his overall experience. In any case, the full objectivity and repeatability may not be guaranteed. As a consequence, the costs associated to the quality sorting at the log yard are considered as high (HAN-SUP *et al*. 2011). Alternative solutions for more efficient sorting were proposed to measure simultaneously lot of logs arranged in stacks (GEJDOS *et al.* 2019, GUTZEIT and VASKAMP 2012). Free vibrations, stress wave velocity or acoustic analysis (TSEHAYE *et al*. 2000) in combination with machine vision (GEJDOS *et al.* 2019, GUTZEIT and VASKAMP 2012) were identified as most suitable.

The highest economic gain and optimal use of raw resources along the supply chain requires decision regarding the resource quality and usage suitability as early as possible. For that reason, some prototype solutions for quality grading aligned with the tree felling by the processor directly at the forest stand were proposed (SANDAK *et al.* 2019). However, till now the automated log sorting methods implemented in the sawmill yard are considered as more practical solution. In majority of state-of-the-art systems dedicated scanners allow measurement of the log dimensions, shape variation and consequently to determine the quality quantifier. This kind of scanning is carried out during the separation of incoming logs (sorting according to dimensional/quality class) or before sawing operation to optimize the sawing pattern. Set of laser triangulation sensors scanning the log from different directions are usually used for raw data acquisition. A great advantage of this approach is minimal requirement regarding the yard area for storing logs as well as capacity for sorting high number of logs with feed speeds up to 200 $m \cdot min^{-1}$ (SIEKIAŃSKI *et al*. 2019). The trend of further upgrade of the log scanners by integrating additional to triangulation measurements is noticeable these days. Machine vision systems working in visible or infrared ranges, light scatter detectors, ultrasonic or microwave scanning modules are combined allowing multi-sensor evaluation and consequently more effective detection of wood defects and/or quality sorting. The latest technological developments provide a possibility to visualize defects in the log interior (such as knots or cracks) that are not visible on the log surface. In that case affordable X-ray radiography module is integrated with industrial scanners (FREDRIKSSON *et al*. 2014). The number of modules may vary from one to a few, resulting in better representation of the raw resource. The X-ray scanning of logs may be extended to the fully functional Computed Tomography (CT) scanners that are capable to real-time measure, grade or optimize logs at full industrial speeds (RAIS *et al*. 2017). The combination of diverse sensing techniques leads to improvement of the produced timber quality. RIDOUTT *et al*. (1999) reported that proper sorting of logs have an impact on the strength of the lumber produced.

The goal of this study was to quantify an effect of the log sorting strategy on the estimated yields and economic gain for the lumber obtained after sawing process in a real case of the middle-sized sawmill. The critical comparison of three alternative sorting schemes was performed with a special emphasis on the variety of constrains common in the industrial environments.

MATERIALS AND METHODS

Materials

Scotch pine (*Pinus sylvestris* L.) logs harvested in the Błędno Forestry, Lubichowo District in the Pomeranian Region in Poland were used as experimental samples. The sample lot corresponded to a typical single transport delivered by logistic operator to the premises of the Sylva sawmill. The wood was ordered from the forest as a large-size logs with dimensions in accordance to PN-92/D-95017 standard, assuming log length L_w = 4 m and a minimum available diameter of the top end without bark d_{top} = 14 cm. The total number of logs in the delivery lot was N_t = 143, however, subset N_a = 60 of logs was randomly selected for the sorting simulation. Each chosen log was marked with a unique number to assure proper tracking and further comparison of results (Figure 1). Microsoft Office Excel 2007 was used for randomized selection of logs. Table 1 presents a list of logs used for experimentation.

Fig. 1 Marked Scotch pine logs ready for sorting operation.

Tab. 1 Identifiers of randomly selected logs used for sorting simulation.

log number (d_{top} - measured with an optical scanner)														
1 (27)	3 (26)	13 (23)	14 (26)	16 (22)	17 (25)	19 (25)	20 (33)	21 (26)	22 (23)	25 (31)	28 (26)	29 (25)	30 (23)	35 (25)
38 (29)	39 (32)	41 (23)	43 (29)	46 (29)	47 (22)	51 (26)	53 (28)	54 (26)	55 (26)	59 (26)	63 (26)	64 (27)	65 (22)	68 (23)
69 (25)	72 (22)	77 (24)	78 (23)	79 (24)	81 (23)	84 (22)	85 (23)	87 (27)	89 (29)	90 (27)	92 (27)	93 (22)	95 (29)	98 (27)
99 (23)	101 (26)	103 (22)	105 (27)	111 (31)	112 (24)	114 (24)	115 (23)	117 (30)	119 (28)	124 (23)	135 (22)	137 (24)	139 (27)	140 (25)

Strategies for log sorting

The lot of experimental logs was subjected to dimensional and qualitative assessment implementing four sorting strategies.

Forester in the forest

The first quality assessment was performed by the certified forest worker who sorted logs to quality classes in accordance with the PN–92/D–95017 and PN–D–95000:2002 standards. The assessment was performed before transporting logs to the sawmill and was a basis for the estimation of the market values of logs. The set of information recorded in the transport documentation included: wood species (Scotch pine), log length (large-size logs with L_w = 4 m) and minimum quality class of log within the lot (class C). The summary of such characteristics as extracted from the formal documentation is presented in Table 2. Unfortunately, due to the lack of tracing procedure for identification of a single log, it was impossible to link this information with a specific logs. Consequently, the formal trade documentation had only limited value for the sawmill sorting operations as the whole procedure must be repeated on-site. In addition, a common practice of the sawmill is to perform debarking operation before sorting and storing logs. The result of debarking is a clean log that allows more precise dimension measurements and better sight to wood defects present on its surface.

Tab. 2 The set of information available to extract from the forest logistics documentation when lot of logs reaches sawmill destination.

Symbol of logs	Quality class	Length. L_w (m)	Diameter. d_{top} (cm)	Quantity (pieces)	Volume. V_{wood} (m^3)
SO - W	A	4.0	31	2	0.66
SO - W	A	4.0	32	1	0.35
SO - W	A	4.0	34	1	0.39
SO - W	B	4.0	23	8	1.52
SO - W	B	4.0	24	5	1.00
SO - W	B	4.0	25	7	1.54
SO - W	B	4.0	26	5	1.20
SO - W	B	4.0	27	6	1.50
SO - W	B	4.0	28	3	0.81
SO - W	B	4.0	29	1	0.29
SO - W	B	4.0	31	1	0.33
SO - W	B	4.0	33	1	0.37
SO - W	C	4.0	20	2	0.28
SO - W	C	4.0	21	9	1.44
SO - W	C	4.0	22	21	3.57
SO - W	C	4.0	23	24	4.56
SO - W	C	4.0	24	12	2.40
SO - W	C	4.0	25	10	2.20
SO - W	C	4.0	26	6	240
SO - W	C	4.0	27	6	1.50
SO - W	C	4.0	28	2	0.54
SO - W	C	4.0	29	3	0.87
SO - W	C	4.0	31	1	0.33
Sum total				141	30.05

Unexperienced person

The set of experimental logs after debarking process was spread out on the storage yard (Figure 2) to allow easy access to each log for taking required measurements. The following assessment was performed by the team of two sawmill workers who were not specifically trained for the quality sorting of logs. Both operators were instructed to perform simple measurements of log dimensions by using standard tools (measuring tape and ruler), including small-end diameter of log d_{top} and its length L_w. The unexperienced employees did not take into account a taper of the logs. In addition, the bulk volume of each log V_{wood} was calculated following equation 1 adopted for determining the volume of a simple cylinder.

$$V_{wood} = \frac{\pi \cdot {d_{top}}^2}{40000} \cdot L_w \quad (1)$$

The unexperienced workers did not sort logs into specific quality classes and therefore the whole lot was assumed to be of same but unknown quality. As a rule, all these logs were destinated for the follow-up sawing operation as a diameter-based sorts where the optimal sawing pattern is defined to maximize the volume of generated products without wood quality consideration.

Fig. 2 Experimental logs ready for manual grading after debarking and spacing on the storage yard.

Certified grading expert

The second mode of sorting was conducted by the certificated grading expert. This experienced employee measured and classified quality of selected logs following rules defined in PN-92/D-95017 and PN-D-95000:2002 standards. The volume of log was estimated with the use of formal tables included in GM-900-7/2013 (Ordinance of General Director of State Forests in Poland no 74) and calculated according to equation 2, considering the log as a bevelled cone with a taper *z*.

$$V_{wood} = \frac{\pi}{40000} \cdot \left(d_{top} + z \cdot \frac{L_w}{2}\right)^2 \cdot L_w \quad (2)$$

In-line automatic scanning system

The scanner JORO-3D-800 produced by Jörg Elektronik GmbH (Oberstaufen, Germany) was used for automatic sorting of experimental logs following the manual quality assessment procedures. It is equipped with three sets of triangulation sensors combined with video cameras. Those are arranged all around the measured log passing through the scanner on the conveyer. The system allows continuous and complete characterization of each log, providing reliable and repeatable sorting decisions derived on the basis of objectively measured log properties. The continuous and high resolution recording of the log surface features allows extraction of several relevant characteristics, such as: diameter, length, ovality, taper, curvature, as well as cross-section's flatness of log ends (Figure 3). The software expert system of the scanner determines the quality class on the basis of all available information collected from each log separately (Web Source 1). However, the grading decision derived by scanner is considered as only a suggestion that has to be confirmed or adjusted by the scanner operator. He was a highly skilled worker supervising the whole sorting line. The operation is able to observe the log appearance before decision. All the data collected from scanning experimental logs were recorded and stored on the computer hard disk for further analysis.

a) b)

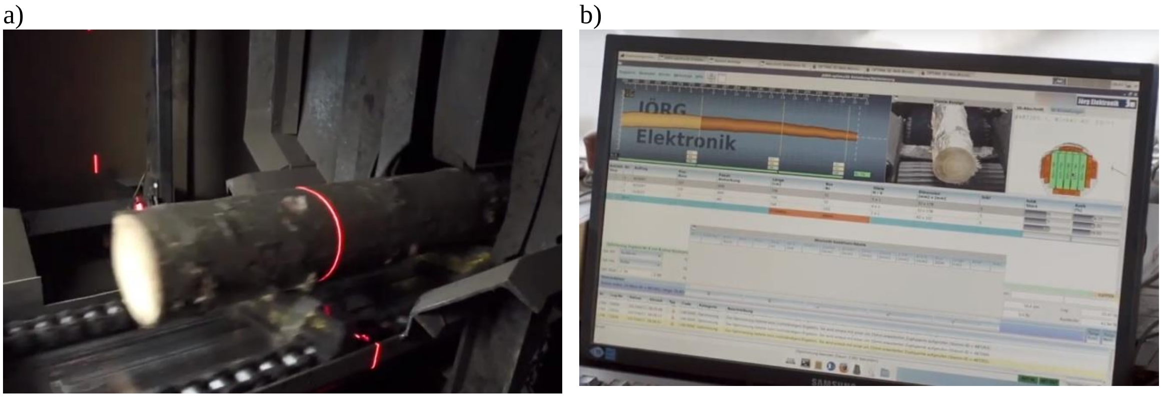

Fig. 3 The in-line automatic scanning system for logs: laser line illuminating the log during scanning (a) and software for controlling, visualization and sorting (b) (Web Source 1).

Optimization of the log sawing pattern

The optimal pattern for sawing logs is critical to assure the best value of produced assortments as well as the highest production volume. Optiscie 2.0 (Etablissements Mauchamp SAS, Quetigny, France) software package was used to determine best sawing strategy for each sorted log. Two product lines are in the portfolio of the sawmill, where timber elements of highest (A) quality are sawn to the thickness of 27 mm, while moderate quality (class *B* and *C*) to the thickness of 52 mm. The kerf width of circular saw S_t used in analysis was 4 mm. Various sawing scenarios were generated assuming dimensional class graduation of the small-end diameter of log d_{top} every 2 cm and the maximum d_{top} = 28 cm. An example of two alternative sawing patterns for logs of diameter class 20.0–21.5 cm for different quality assortments are presented in Figure 4. The width of each board matched the allowed dimension matrices defined by production engineers of the Sylva sawmill.

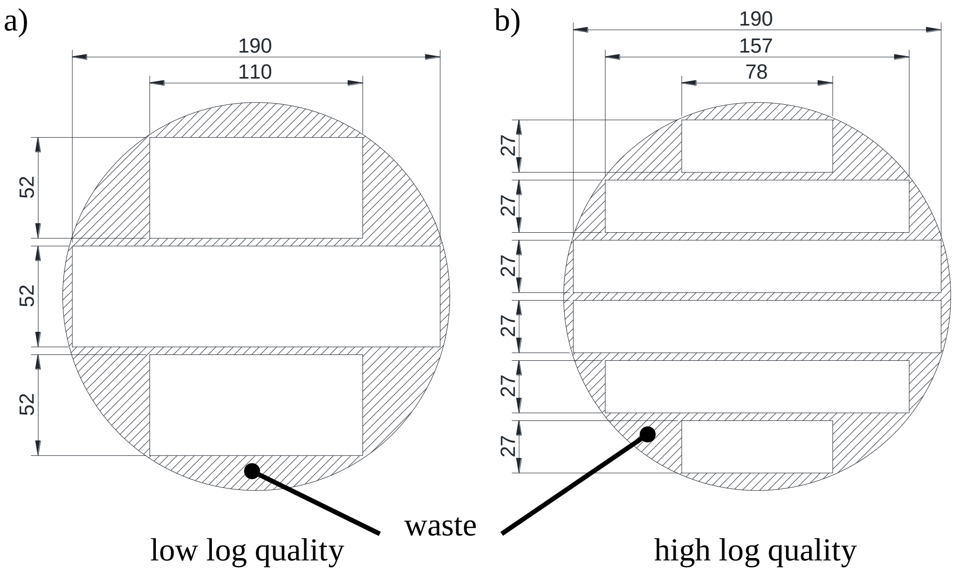

Fig. 4 Examples of alternative sawing patterns used for processing logs of varying quality but corresponding top diameter (range from 20 to 21.5 cm).

RESULTS AND DISCUSSION

Comparison of the cumulative volume V_{logs} of sorted pine logs estimated after implementing three diverse sorting scenarios is shown in Figure 5. It is evident that the volume of logs measured by the grading expert corresponds to that estimated by the optical scanner. The result of the cumulative volume obtained from the measurements performed by an unexperienced employee was clearly differencing from other approaches. This is related to the taper of logs neglected when calculating volume (equation 1). The summary of all log characteristics as measured by both workers, not skilled and expert, is reported in Table 3.

The sorting time is an important issue increasing overall operational costs of the sawmill. The result of this research indicates that it varied considerably in each studied scenario. The optical scanner realizes sorting process with conveyor feed speed of 100 m·min^{-1}. The unit sorting time t_u for logs of length L_w = 4 m, and with a standard distance between logs on the conveyor 2 m, corresponds to t_u = 3.6 seconds per single log. The sawmill worker's time necessary for the loading of the sorting line with logs from the entrance pile as well as unloading of sorted logs from the collection boxes should be taken into consideration when estimate the total cost of the sorting operation. This is defined as preparatory and finishing time t_{pf} that in the case of present study was estimated at 15 minutes (0.25 hour) for the lot of 60 logs (FELD 2003). The time t_{pf} increases even more to 30 minutes (0.50 hour) for manual sorting operations due to the necessity of spreading logs over the wide area before sorting and following collection along with separations of graded logs. It was noticed that the average time for quality sorting of a single log by the grading expert varied between 30 to 60 seconds, depending on the extent of wood defects and overall log quality. Therefore, an average value (t_u = 45.0 seconds) was adopted for the following calculations. The worker without experience required approximately 15.0 seconds for each log to properly measure its dimensions. It is possible to express the sorting efficiency as a log sorting rate (*LSR*) indicator, computed as a ratio of the sorted logs volume and cumulative time necessary for this operation (equation 3). The resulting *LRS* for three tested sorting scenarios are shown in Figure 6.

$$LSR = \frac{V_{logs}}{t_{pf}+(N_a \cdot t_u)} \qquad (3)$$

Fig. 5 The estimated total volume of sorted pine logs assessed with three sorting scenarios.

Despite the fact that the certified grading expert measures logs dimensions and determines their volume with similar accuracy as the optical scanner, the automatic system realizes the sorting process four times faster.

Tab. 3 Technical characteristics of pine logs assessed during sorting with three alternative scenarios.

Number of wood log	unexperienced worker			grading expert			in-line scanner		
	Length of log (cm)	Top diameter of log (cm)	Volume of log (m^3)	Length of log (cm)	Top diameter of log (cm)	Volume of log (m^3)	Length of log (cm)	Top diameter of log (cm)	Volume of log (m^3)
1	410	26	0.218	410	25	0.225	411	27	0.212
3	409	24	0.185	409	24	0.208	408	26	0.229
13	409	23.5	0.177	409	23	0.192	408	23	0.181
14	411	25	0.202	410	25	0.225	409	26	0.229
16	410	22.5	0.163	410	22	0.177	409	22	0.166
17	412	24	0.186	409	24	0.208	412	25	0.212
19	411	25	0.202	410	24	0.208	409	25	0.212
20	412	32	0.331	411	32	0.361	412	33	0.342
21	410	25	0.201	409	24	0.208	409	26	0.212
22	415	24	0.188	415	23	0.195	413	23	0.196
25	409	31	0.309	407	31	0.336	407	31	0.322
28	410	27.5	0.244	409	27	0.260	409	26	0.229
29	410	24.5	0.193	409	24	0.208	409	25	0.196
30	410	21	0.142	407	20	0.147	406	23	0.181
35	412	26	0.219	412	25	0.226	411	25	0.246
38	410	28	0.252	410	27	0.260	410	29	0.264
39	409	30	0.289	409	29	0.297	408	32	0.342
41	410	22	0.156	410	22	0.177	409	23	0.166
43	410	29	0.271	409	29	0.297	409	29	0.302
46	414	28.5	0.264	413	27	0.262	413	29	0.283
47	412	22	0.157	411	22	0.177	411	22	0.166
51	413	25.5	0.211	413	25	0.227	414	26	0.235
53	411	28	0.253	410	28	0.279	410	28	0.264
54	411	26.5	0.227	411	25	0.226	410	26	0.229
55	410	26	0.218	410	25	0.225	411	26	0.229
59	412	26	0.219	411	25	0.226	411	26	0.229
63	411	26.5	0.227	410	26	0.242	407	26	0.229
64	408	26	0.217	409	26	0.242	407	27	0.264
65	410	22.5	0.163	411	21	0.163	409	22	0.166
68	408	23	0.170	410	22	0.177	410	23	0.181
69	412	25	0.202	411	25	0.226	411	25	0.229
72	408	22	0.155	407	22	0.175	405	22	0.181
77	411	24.5	0.194	410	24	0.208	410	24	0.212
78	411	23	0.171	410	23	0.192	410	23	0.181
79	412	24	0.186	410	23	0.192	409	24	0.181
81	411	24	0.186	411	24	0.209	410	23	0.196
84	412	22	0.157	410	21	0.162	410	22	0.166
85	411	22	0.156	411	22	0.177	410	23	0.181
87	409	27	0.234	409	27	0.260	408	27	0.264
89	409	29	0.270	409	27	0.260	409	29	0.283
90	408	27	0.234	409	26	0.242	409	27	0.264
92	409	26	0.217	408	25	0.224	409	27	0.246
93	409	23	0.170	408	22	0.176	408	22	0.196
95	408	29	0.269	407	28	0.277	407	29	0.264
98	409	27	0.234	408	27	0.259	407	27	0.246
99	411	23.5	0.178	409	23	0.192	410	23	0.166
101	412	26	0.219	412	25	0.226	411	26	0.229
103	412	21.5	0.150	411	22	0.177	411	22	0.181
105	410	26	0.218	410	26	0.242	410	27	0.229
111	409	32	0.329	409	31	0.338	408	31	0.322
112	410	25	0.201	409	24	0.208	409	24	0.212
114	413	23	0.172	411	23	0.193	411	24	0.181
115	411	22	0.156	410	22	0.177	409	23	0.181
117	411	29	0.271	410	29	0.298	410	30	0.283
119	411	32	0.331	410	27	0.260	410	28	0.246
124	409	24	0.185	409	21	0.162	408	23	0.166
135	412	22	0.157	412	22	0.178	411	22	0.166
137	410	23	0.170	409	23	0.192	408	24	0.196
139	412	26	0.219	412	25	0.226	409	27	0.229
140	411	26	0.218	410	26	0.242	412	25	0.212
sum of wood logs volume			**12.660**			**13.410**			**13.403**

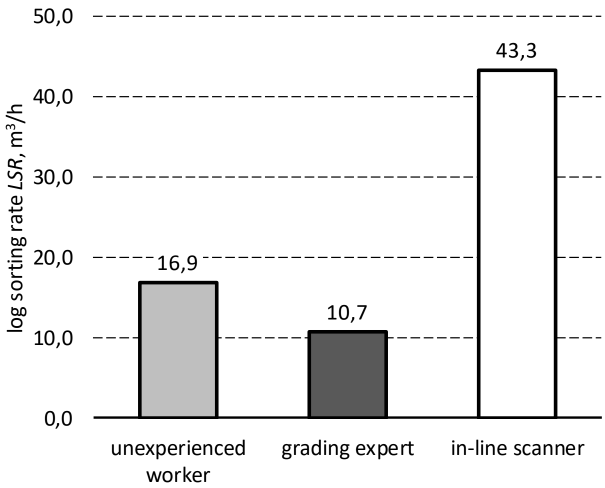

Fig. 6 Log sorting rate *LSR* of pine logs assessed with three sorting scenarios.

The optimal sawing patterns for each log quality-dimension combination as determined for logs with diameter d_{top} in the range from 20.0 to 29.5 cm are summarized in Table 4. The upper part of the table includes recommended boards distribution for the best quality logs (class *A*), while bottom part to moderate quality logs (class *B* and *C*). The list of cross sections for sawn boards corresponds to those in the Sylva sawmill portfolio frequently used in down-stream production or direct sells to clients.

Tab. 4 Optimized sawing patterns for pine logs in relation to the log diameter and its quality class.

cross section of board (mm × mm)	number of boards at the log cross section				
	quality class *A*				
	$20.0<d_{top}<21.5$	$22.0<d_{top}<23.5$	$24.0<d_{top}<25.5$	$26.0<d_{top}<27.5$	$28.0<d_{top}<29.5$
27 × 78	2	-	-	-	2
27 × 105	-	-	2	-	-
27 × 131	-	2	-	2	-
27 × 157	2	-	-	-	-
27 × 178	-	2	2	-	2
27 × 190	2	-	-	-	-
27 × 205	-	-	-	2	-
27 × 210	-	2	-	-	-
27 × 215	-	-	3	-	-
27 × 240	-	-	-	3	2
27 × 260	-	-	-	-	3
	quality class *B* and *C*				
52 × 103	-	-	2	-	-
52 × 110	2	-	-	-	-
52 × 140	-	2	-	2	-
52 × 178	-	-	-	-	2
52 × 190	1	-	-	-	-
52 × 215	-	1	2	-	-
52 × 235	-	-	-	2	-
52 × 260	-	-	-	-	2

Even if the volume of logs estimated by the grading expert and in-line scanner are similar, the differences due to assigned quality class are noticeable (Table 5). The expert identified only 2 logs as fulfilling requirements for assignment to the superior quality class *A*. Conversely, in-line scanner graded 51 logs as belonging to the quality class *A*, though none to class *C*. The discrepancy is related to different grading rules used for the sorting decision. These codified by standards are more rigorous than the expert system rules implemented in the optical scanner. Another source of divergence is inability for detailed identification of knots by the scanner, combined with subjective evaluation of the scanner operator that have very limited time to rectify suggestion of the automatic grading system. Presence and excessive size of knots was the most frequent criteria that forced the expert to downgrade the log quality class.

Tab. 5 Quality classes of graded logs and forecasted total volume of produced timber.

	number of assigned logs (pcs)		
	unexperienced worker	grading expert	in-line scanner
A	0	2	51
B	0	19	9
C	60	39	0
	total volume of timber with specified thickness (m^3)		
	unexperienced worker	grading expert	in-line scanner
27 mm	0.000	0.392	7.855
52 mm	8.572	7.756	1.177
Σ	8.572	8.148	9.032

Both, the number of logs as well as the total volume of timber forecasted to be produced from logs sorted according to three studied scenarios differed noticeably (Table 5). The lack of quality information assessed by the unexperienced worker results in downgrading of all logs to the quality class *C*. As a consequence, all these logs should be processed in the sawmill to thick (52 mm) boards considering only the small-end diameter of log d_{top} as a criteria for the selection of optimal sawing pattern. Even that, the total volume of the produced timber was higher than of elements sawed according to sorting decisions provided by the grading expert. It was an unexpected result, as according to the adopted sawmill procedures, both quality class *B* and *C* are considered as an equivalent resource and follow the same transformation path. Therefore, 58 (of 60) logs defined by the grading expert as not superior class *A* should be processed same way as logs assessed by unexperienced worker. The observed discrepancy in the total volume may be therefore caused by the measurement faults introduced by the unexperienced worker. The erroneous measurement of the log's small diameter substantially affects the selection of the sawing pattern and consequently total volume of derived timber.

Quality sorting of studied logs by the in-line scanner resulted in a high number of logs considered as superior quality. As a consequence, these were processed as more valuable timber components of the smaller board thickness (27 mm). It resulted in the overall yield increase of ~0.9 m^3, compare to yield obtained from logs sorted by the grading expert. This difference was caused by a higher recovery of timber products of smaller thickness. The waste area, corresponding to material losses, is considerably smaller in case of sawing 27 mm thick boards than that of 52mm, as can be noticed in Figure 4. Another advantage of thinner boards is a higher variety of allowed board widths accepted by the sawmill managers for sawing. It was doubled compare to boards of 52 mm thickness (Table 4). It permits even better optimization of the sawing pattern and further reduction of the wasted wood, despite greater losses on kerfs of saw blades.

The material yield recovered from logs after sawing process is an important quantifier of the production efficiency. However, it is the monetary value that determines economic sustainability of the sawmill.

Tab. 6 Quality class, expected timber volume and its value simulated for all experimental logs and three alternative sorting scenarios.

number of log	unexperienced worker			grading expert			in-line scanner		
	quality class of log	expected lumber volume (m^3)	expected lumber value (PLN)	quality class of log	expected lumber volume (m^3)	expected lumber value (PLN)	quality class of log	expected lumber volume (m^3)	expected lumber value (PLN)
1	C	0.160	85.71	C	0.136	72.68	A	0.154	99.32
3	C	0.135	72.50	C	0.135	72.50	A	0.153	98.60
13	C	0.105	56.43	C	0.105	56.43	A	0.137	88.40
14	C	0.136	72.86	C	0.136	72.68	A	0.154	98.84
16	C	0.106	56.57	C	0.106	56.57	A	0.138	88.62
17	C	0.136	73.03	C	0.135	72.50	A	0.135	86.62
19	C	0.136	72.86	B	0.136	72.68	A	0.134	85.99
20	C	0.188	100.59	A	0.197	126.44	A	0.197	126.75
21	C	0.136	72.68	C	0.135	72.50	A	0.154	98.84
22	C	0.137	73.57	B	0.107	57.26	A	0.138	88.62
25	C	0.186	99.86	C	0.185	99.37	B	0.185	99.37
28	C	0.160	85.71	C	0.160	85.50	A	0.154	98.84
29	C	0.136	72.68	B	0.135	72.50	A	0.134	85.99
30	C	0.087	46.85	C	0.087	46.51	B	0.087	46.40
35	C	0.161	86.12	B	0.136	73.03	A	0.134	86.41
38	C	0.187	100.11	B	0.160	85.71	A	0.196	126.13
39	C	0.186	99.86	B	0.186	99.86	A	0.195	125.52
41	C	0.106	56.57	C	0.106	56.57	A	0.138	88.62
43	C	0.187	100.11	B	0.186	99.86	A	0.196	125.82
46	C	0.189	101.08	B	0.161	86.33	A	0.198	127.05
47	C	0.106	56.84	C	0.106	56.70	A	0.138	89.05
51	C	0.137	73.21	B	0.137	73.21	A	0.156	100.05
53	C	0.187	100.35	B	0.187	100.11	A	0.196	126.13
54	C	0.160	85.92	B	0.136	72.86	A	0.154	99.08
55	C	0.160	85.71	B	0.136	72.68	A	0.154	99.32
59	C	0.161	86.12	C	0.136	72.86	A	0.154	99.32
63	C	0.160	85.92	C	0.160	85.71	A	0.153	98.36
64	C	0.159	85.29	C	0.160	85.50	B	0.159	85.08
65	C	0.106	56.57	C	0.088	46.97	A	0.138	88.62
68	C	0.105	56.29	C	0.106	56.57	A	0.138	88.83
69	C	0.136	73.03	C	0.136	72.86	A	0.134	86.41
72	C	0.105	56.29	C	0.105	56.15	A	0.136	87.75
77	C	0.136	72.86	C	0.136	72.68	A	0.134	86.20
78	C	0.106	56.70	C	0.106	56.57	B	0.106	56.57
79	C	0.136	73.03	C	0.106	56.57	A	0.134	85.99
81	C	0.136	72.86	C	0.136	72.86	A	0.138	88.83
84	C	0.106	56.84	C	0.087	46.85	A	0.138	88.83
85	C	0.106	56.70	C	0.106	56.70	B	0.106	56.57
87	C	0.160	85.50	B	0.160	85.50	A	0.153	98.60
89	C	0.186	99.86	B	0.160	85.50	A	0.196	125.82
90	C	0.159	85.29	C	0.160	85.50	B	0.160	85.50
92	C	0.160	85.50	C	0.135	72.32	B	0.135	72.50
93	C	0.105	56.43	C	0.105	56.29	B	0.105	56.29
95	C	0.186	99.62	C	0.185	99.37	A	0.195	125.21
98	C	0.160	85.50	C	0.159	85.29	A	0.153	98.36
99	C	0.106	56.70	B	0.105	56.43	A	0.138	88.83
101	C	0.161	86.12	B	0.136	73.03	A	0.154	99.32
103	C	0.088	47.08	C	0.106	56.70	A	0.138	89.05
105	C	0.160	85.71	C	0.160	85.71	A	0.154	99.08
111	C	0.186	99.86	A	0.196	125.82	A	0.195	125.52
112	C	0.136	72.68	B	0.135	72.50	A	0.134	85.99
114	C	0.106	56.98	B	0.106	56.70	A	0.134	86.41
115	C	0.106	56.70	C	0.106	56.57	A	0.138	88.62
117	C	0.187	100.35	C	0.187	100.11	A	0.196	126.13
119	C	0.187	100.35	B	0.160	85.71	A	0.196	126.13
124	C	0.135	72.50	C	0.087	46.74	A	0.137	88.40
135	C	0.106	56.84	C	0.106	56.84	A	0.138	89.05
137	C	0.106	56.57	C	0.105	56.43	A	0.133	85.78
139	C	0.161	86.12	C	0.136	73.03	B	0.135	72.50
140	C	0.160	85.92	C	0.160	85.71	A	0.135	86.62
total value of timber (PLN)			**4594.43**			**4409.65**			**5681.44**

A detailed simulation of the hypothetical market value of timber products obtained from logs sorted according to three investigated scenario was performed within framework of this research. As mentioned before, thinner boards have higher commercial value that corresponded to 643 PLN/m^3. Conversely, the value of thicker boards (52 mm) was 536 PLN/m^3. It is expected therefore that higher price of products combined with the greater predicted volume of timber derived from logs sorted by in-line scanner results in higher value of the produced timber. It is confirmed in Figure 7, where the predicted economic gain is ~30% higher for logs sorted by the in-line scanner, compare to logs graded manually by workers. This is in agreement with other technical reports where implementation of triangulation scanners resulted in considerable increase of the sawmill sorting capacity and improvement in supply of logs with quality properly adjusted for production of floorboards (SIEKANSKI *et al.* 2019).

The commercial value of timber obtained after sawing logs sorted by the grading expert was slightly less than of unexperienced worker. It is a consequence of both, the adopted sawmill strategy to not differentiate quality classes *B* or *C*, and the overestimation of overall logs volume as predicted by the worker. It is important to emphasize that this economic simulation reflects only a hypothetical case representing particular perspective of the Sylva sawmill. The actual value of timber can be only determined after proper log sawing and following quality grading of boards resulted by that process. The summary of quality, expected timber volume and estimated value of derived products for all simulated logs is presented in Table 6.

Fig. 7 The market value of assortments produced by the sawmill when implementing three diverse log sorting scenarios. The exchange rate of Euro (1 EUR = 4.30 PLN) according to the National Bank of Poland as at 26th November 2019.

CONCLUSIONS

The log sorting strategy has a tremendous impact on the sawmill efficiency. Three diverse approaches were investigated here to determine optimal solution for upgrading the current log sorting routines in the middle size sawmill in Poland. It was clearly demonstrated that in-line scanner equipped with triangulation sensors for the external log geometry assessment allows most accurate prediction of the log volumes as well as improves overall reliability of the quality grading. The automatic sorting system increased productivity by a factor of four. An integration of the scanner with the production process in Sylva sawmill was identified as the most profitable solution recommended for advancing current manufacturing process.

The quality sorting of logs by unexperienced worker is not an optimal solution as it results in biased volume estimation as well as low sorting rate.

A full advantage of the grading expert involvement in the routine sorting of logs was not properly explored due to the simulation constrains. There was not defined in the Sylva company any specific path to explore a moderate quality logs (such as class *B*). That class was a frequent grade assigned by the expert to investigated logs. The direct comparison with the other sorting strategies was very limited as a set of grading rules defined in standards is very conservative and strict. As a consequence the sorting results are hardly comparable between three sorting strategies investigated.

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