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Reviewed and accepted for publication in Holz.
als Roh- und Werkstoff.

Simulated and realised industrial yields in the sawing of maritime pine (*Pinus pinaster* Ait.)

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Acknowledgements: Financial support was given to the first author by a scholarship from Fundação para a Ciência e Tecnologia (Portugal) and by a Marie Curie Research Training Grant within the EU 4th RTD Framework programme. Part of the work was carried out under the research programme PAMAF 8185, financed by INIA (Instituto Nacional de Investigação Agrária, Portugal). Thanks are due to the Portuguese National Forest Service (Direcção Regional Agrária da Beira Litoral) and to SONAE Indústria and AJI Serração, who supplied the trees and, in the last case, supported the industrial study. Special thanks are due to Tiecheng Song from VTT for all the necessary adaptations in the reconstruction programme.

Abstract: A sawing simulation software was evaluated by comparison with a real situation in the industrial sawing of maritime pine (*Pinus pinaster* Ait.) stems. At an operational sawmill sawing yields were measured for the conversion of logs with two sawing patterns: production of boards and production of boards and lumber. The simulation used the WoodCIM® optimisation software with similar sawing set-ups and dimensionally matching virtual logs obtained from cross cutting of 3D mathematical reconstructions of maritime pine stems. The virtual maritime pine stems and the sawing simulation software showed potential to evaluate the impact of raw material and process characteristics on the production performance. The simulated sawing yields corresponded closely to the industrial yields for the production of boards (57% volume yield). For production of lumber and boards, the simulation allowed to obtain a higher volume (45% vs. 53%). The negative impact of resin production on the sawing yields was estimated by comparing the industrial yields of resin tapped trees with matching virtual logs and showed to lead to a loss of 11% sawn wood volume, and increasing with log diameter.

1 INTRODUCTION

The efficiency of the sawing process has always been a key issue for the optimisation of the whole wood conversion chain where the primary and secondary conversion industries provide the link between customer's needs and forest production.

The development of machine vision systems and of sawing simulation models has provided tools that can be used to test different scenarios in a virtual world, thereby supporting product and production research and creating information for management, decision-making and process control.

A good model for the wood raw material is required for a virtual sawing capable of predicting quality distribution of the sawn products resulting from the conversion simulations. Progress in scanning technology, defect detection and algorithms for virtual reconstruction of logs allows to study tree shape and internal structure *i.e.* knot, heartwood and resin pockets (Oja 1997; Bjorklung 1999; Pinto et al. 2003, 2004) providing support to improve optimisation and simulation procedures.

During the past 30 years there has been a strong development in optimisation studies of the wood conversion chain with a close interaction between research centres and industry. Wood sawing simulators have been designed and improved in order to reach an accurate virtual wood conversion chain linking raw material properties to industrial production and products, for planning purposes (Hallock et al. 1978, Leban and Duchanois 1990, Schmoldt et al. 1996, Todoroki 1996, Usenius 1999). The impact on sawing yields of specific conversion variables and scenarios has been analysed using the virtual sawing of logs and trees (Richards 1973, Todoroki 1994, Maness and Lin 1995, Pinto et al. 2002, Ikonen et al. 2003).

However, for an efficient use of the information provided by models and simulations it is important to evaluate the differences between the results obtained in the real practice and the simulated outputs. Only few studies have been presented in the literature dealing with this subject. Grundberg (1999) compare the results of a virtual sawmill with the real sawing and manual grading at a single-log level. This sawing simulation system was also validated against a 1-year production of a medium size sawmill (Chiorescu and Grönlund, 2003).

The objective in this study was to evaluate the performance of a sawing simulation software (WoodCIM®) with maritime pine logs (*Pinus pinaster* Ait.) by comparison of the predicted output with a real situation from an operational sawmill, where production yields were measured (Knapic et al. 2004). WoodCIM® is an integrated optimising software system, developed at VTT - Technical Research Centre of Finland (Usenius 1999, 2000). The module for sawing simulation has been adapted for maritime pine and used to study potential sawing yields in different scenarios for this species (Pinto et al. 2002, 200_). The input raw material for the simulations was virtual logs cross-cut from maritime pine stems that were 3D mathematical reconstructions, based on scanned images of flicthes, including the representation of internal knots and heartwood (Pinto et al 2003, 2004). Similar sawing set-ups were used in the simulation runs as in the sawmill and the predicted yields were compared with those effectively obtained.

2 MATERIAL AND METHODS

A sample of maritime pine *(Pinus pinaster* Ait.) stems was selected, cross-cut into logs and sawn at a Portuguese sawmill. Sawing yields were measured at the mill (Knapic et al. 2004) and compared with yields obtained by simulating the sawing of a similar sample of logs selected from a virtual pool of 3D reconstructed maritime pine stems. The bucking and sawing simulation modules of WoodCIM® were used after adaptation for this species (Pinto et al. 2002). Figure 1 shows the main steps of the comparison between industrial and simulated sawing yields.

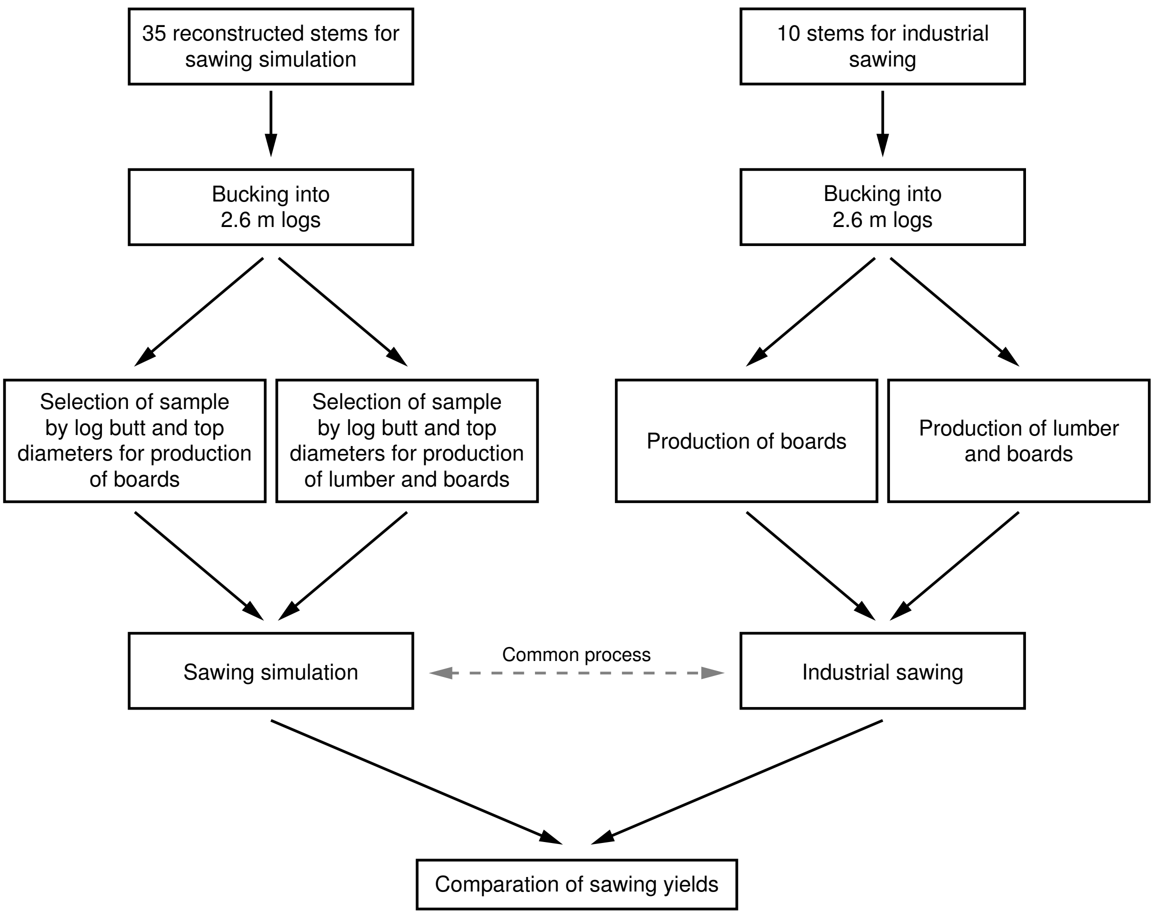

Figure 1: Main steps for the industrial and sawing tests

2.1 Industrial sawing
2.1.1 Raw material
A sample of ten trees of maritime pine was randomly chosen from a stand in Portugal. Six trees were resin-tapped and showed the wounding streaks in the lower part of the stem. The trees were bucked and cross-cut into logs of different lengths according to their final end uses. For this study only 2.6 m logs were taken as used in the production of boards and lumber. Tree and log characteristics are described in Table 1.

Table 1: Sample tree biometry and main log parameters for industrial and simulation study (Average plus SDEV)

	Industrial test	*Virtual test*
Sampled Trees		
Number	10	35
Age	70 (8)	69 (17)
DBH (cm)	34.6 (4.1)	43.0 (9.6)
Height (m)	19.3 (2.1)	25.4 (5.0)
Volume(1) (m^3)	0.5 (0.2)	1.7 (0.9)
Sawlogs		
Number	29	218
Diameter butt (mm)	280.2 (58.1)	305.0 (89.0)
Diameter top (mm)	241.3 (32.9)	281.3 (81.3)
Taper(2) (mm/m)	9.4 (7.8)	9.9 (6.4)
Volume(3) (m^3)	0.1 (0.1)	0.2 (0.1)

(1) Volume under bark - Smallian formula
(2) Slope of the line marking the external limit of diameters determined every 50 mm of length
(3) Volume under bark

2.1.2 Sawing
Two sawing patterns were used (Figure 2): single production of boards or mixed production of boards and lumber (centre pieces). The boards were cut with the maximum allowed width. The products dimensions are indicated in Figure 2. The first cut was made with the head ridge saw on a direction parallel to the log axis, *i.e.* live sawing. The second cut edged the boards and lumber in order to avoid any wane, being responsible for the correct board width and lumber thickness. The third cut squared the end of the sawn pieces at the final length.
The production yield was calculated by taking measurements at a series of critical points along the production line. After the first cut, thickness and width were measured every 5 cm along the sawn products. The same procedure was repeated after the second and third cuts, but only one measure was taken due to the geometry of the products. The production yield was calculated as the proportion of the final production volume in the total raw material volume, based on the green dimensions. Log volume was calculated geometrically as a truncated cone with butt and top diameter measurements.

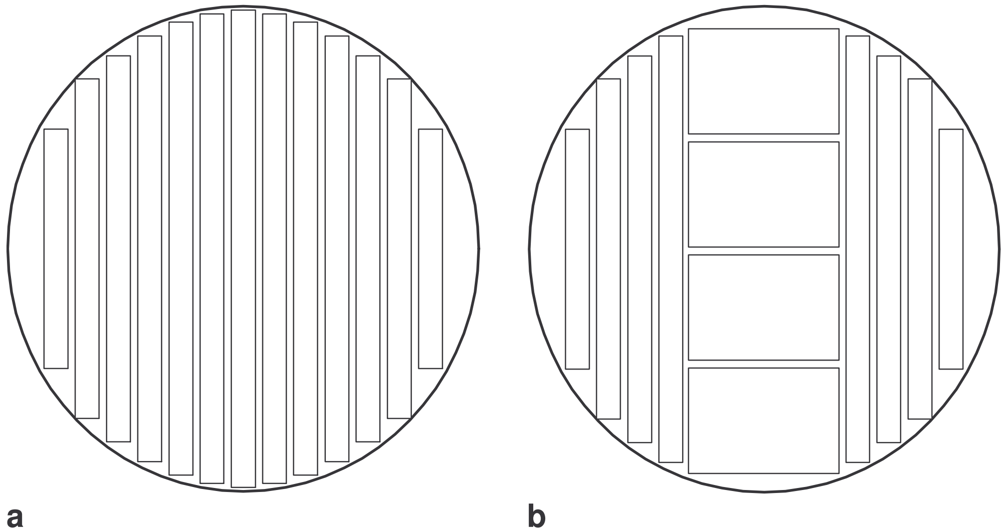

Figure 2: Sawing patterns – Single production of boards (2a) and mixed production of lumber and boards (2b). Lumber dimensions: 50/70 x 100 x 2500 mm. Board dimensions: 25 x 90 - 250 (each 5 mm) x 2500 mm. Saw kerf: 2.5 mm.

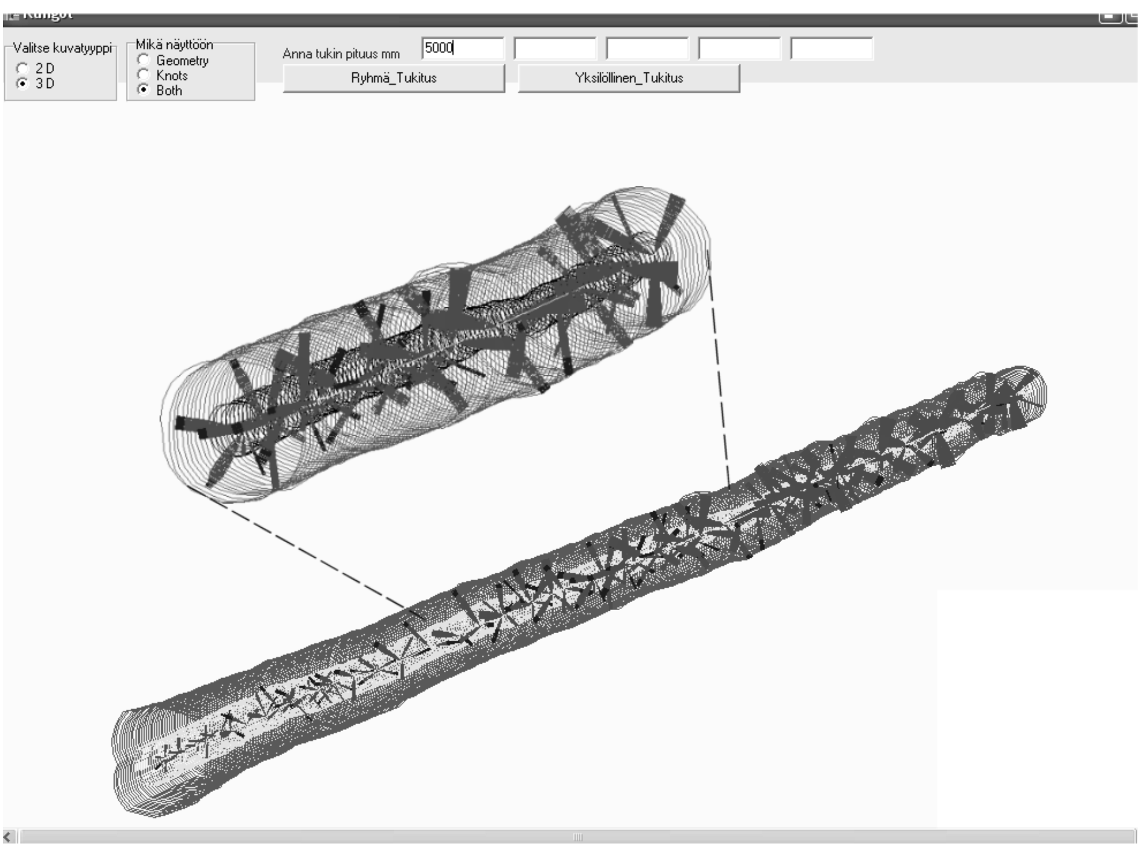

Figure 3: 3D representations for one maritime pine stem and one bucked log

2.2 Virtual sawing

2.2.1 Sampling raw material

The sawing simulation was made with logs selected from a set of 35 virtual 3D stems, which were mathematical reconstructions of maritime pine trees randomly harvested from four stands in Portugal. Data concerning forest stand and tree biometry were detailed in Pinto et al. (2004). The virtual representation of the maritime pine stems was based on the computing of scanned images of flitches (Song 1987,1998, Usenius 1999) and included geometrical and quality features (*i.e.* heartwood and knots) as described in detail in Pinto et al. (2003, 2004). Figure 3 exemplifies the 3D representations for one maritime pine stem and one bucked log.

For this study the 35 maritime pine reconstructed stems were cross-cut with the bucking module of WoodCIM® at a 2.6 m length into a total of 218 logs. In the description of the external shape the reconstruction gives as output 24 radial vectors per each cross-section of the log with a between cross-section distance of 50 mm. The diameter was calculated with the average of all vectors that define each cross-section. The log volume was calculated by the sum of volumes of successive 50 mm sections. Tree and log characteristics are described in Table 1.

To compare the sawing simulation with the industrial results, a sample of 29 logs was chosen, from the 218 virtual logs pool, based on equivalent butt and top diameters. Figure 4 displays the diameters of the real and virtual logs.

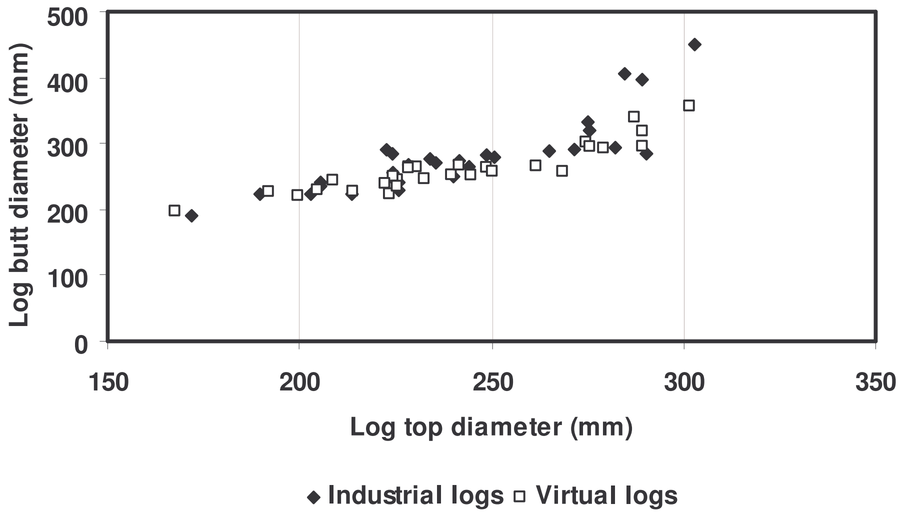

Figure 4: Log top and butt diameters for the industrial logs and the selected virtual logs

2.2.2 Sawing simulation

The sawing simulation software of WoodCIM® was used to predict the production output of boards and lumber. The programme uses different sawing set-up options for each log and chooses the best combination of sawing pattern, dimensions and qualities of the sawn timber products. The input variables are the nominal and green dimensions of sawn timber products, the quality requirements for each face, prices of sawn timber products and of co-products and saw kerfs. The software was adapted for maritime pine, *i.e.* in the input data the number of sawing patterns was increased to 100 and the number of widths allowed to each sawn product was increased from 5 to 35. The sawing method is live-sawing with fixed rotation position of the log in which is maintained in the different sawing simulations of the log.

The output gives the best set-up and sawing pattern, the number of sawn timber products by dimension and grade and the volume and value yield of sawn timber products for the entire batch of logs, for the logs of one stem, for individual logs and for a specified log sample.
For this study, the input data for the simulations concerning product dimensions, sawkerf and sawing patterns was equivalent to those used in the industrial test (Figure 2,). No wane edge was allowed in any sawing product. Only green dimensions were used and green sawing yields were obtained, as in the industrial tests. The simulation program was run to make volume optimisation by setting equal quality and prices to all products.
For the simulation of board sawing the software was modified to edge each individual board with the maximum width as it was done in the industrial edging operation (Figure 2). For sawing lumber and boards, 40 different sawing patterns were given as input with the lumber pieces taken from the central part of the log and boards from the sides. For this simulation, board width and thickness were inputted in cross fields so the industrial pattern could be reproduced (Figure 2b).

3 RESULTS

3.1 Single sawing pattern: boards

The batch yield for the simulated sawing of the 20 virtual logs for production of boards was similar to the industrial yield (Table 2). However, the yields obtained in the sawmill for individual logs showed a larger range of variation, from 36% to 76% in the industrial test and from 45% to 64% in the virtual sawing. Figure 5 registers the spreading of individual log yields by log top diameter. For smaller logs industrial yield is in general higher than the simulated one. However, for bigger logs the highest absolute differences occur when the sawing simulated yield was higher than the industrial one.
In the pool of virtual logs, the number of logs with butt and top diameters matching those of the industrial logs was 89. A simulation run with these logs resulted into yields similar to those obtained with the 20 log samples: batch yield 54% ranging for individual logs from 38% to 65%.

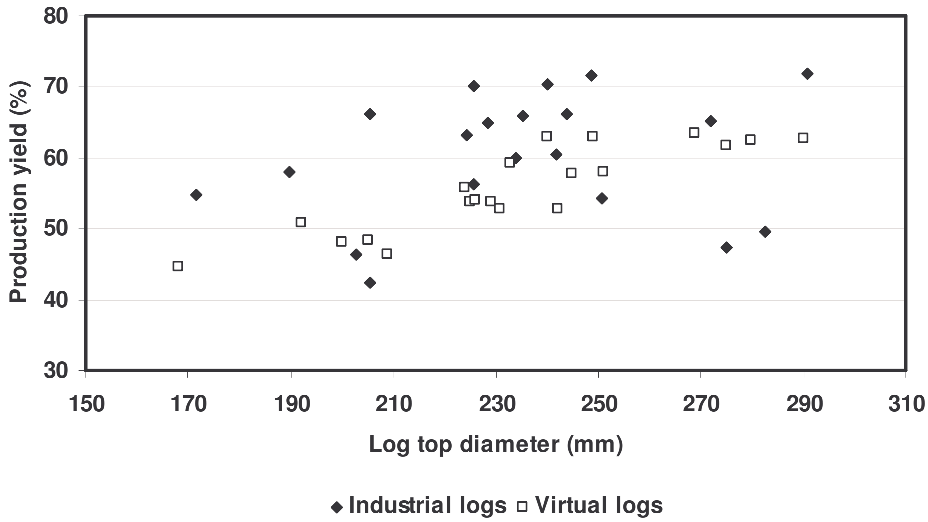

Fig 5: Sawing yields for the industrial and virtual logs

Table 2: Industrial and simulated sawing outputs

	Industrial Logs	*Virtual Logs*
Sawing for boards		
Number	20	20
Butt diameter (mm)	190 - 454	200-307
Top diameter (mm)	172 - 303	168-290
Taper (mm/m)	0.2-22	3.9-23.5
Minimum yield (%)	35.7	44.6
Maximum yield (%)	76	63.5
Batch yield (%)	*56.8*	*56.6*
Sawing for lumber and boards		
Number	3	3
Butt diameter (mm)	224-289	229-268
Top diameter (mm)	214-265	214-266
Taper (mm/m)	9-17.8	2.8-5.4
Minimum yield (%)	43	47.3
Maximum yield (%)	47	58.7
Batch yield (%)	*44.7*	*52.7*
Sawing resin tapped logs		
Number	6	6
Butt diameter (mm)	285-454	243-362
Top diameter (mm)	223-303	223-302
Taper (mm/m)	0.4-24.7	4.2-23.5
Minimum yield (%)	32.8	52.4
Maximum yield (%)	61.5	58.9
Batch yield (%)	*44.1*	*55.1*

The variation of batch sawing yield with the number of logs included in the sample is shown in Figure 6 for the industrial test and the simulation, where the number of logs in the sample is increased randomly by one log. The yields were very variable for a batch with a small number of logs but from 10 logs up the yields appeared to stabilize and showed similar variation for simulation and industrial test. When 18 or more logs were included in the sawing batch, the industrial and simulated yields became very close.
Figure 7 shows the width distribution of the sawn boards. A large range was obtained with the highest frequency for widths between 190 and 210 mm, respectively 21 and 27% for the virtual and industrial cases. Some differences were observed between simulation and industrial run, with more boards with larger widths for the simulated sawing: 64% of the boards obtained with the sawing simulation of the 20 virtual logs had widths between 190 and 270 mm, while the corresponding proportion was only 46% in the industrial sawing.

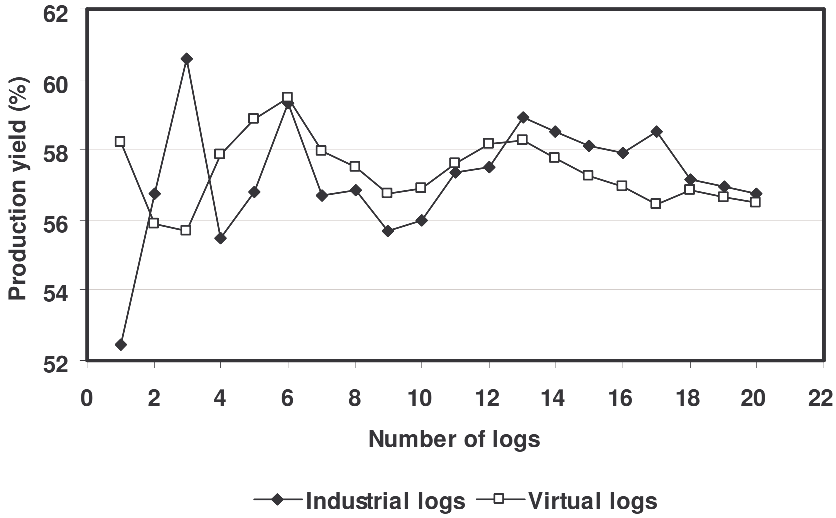

Figure 6: Variation of batch yields with the number of logs for the industrial and the simulated sawing

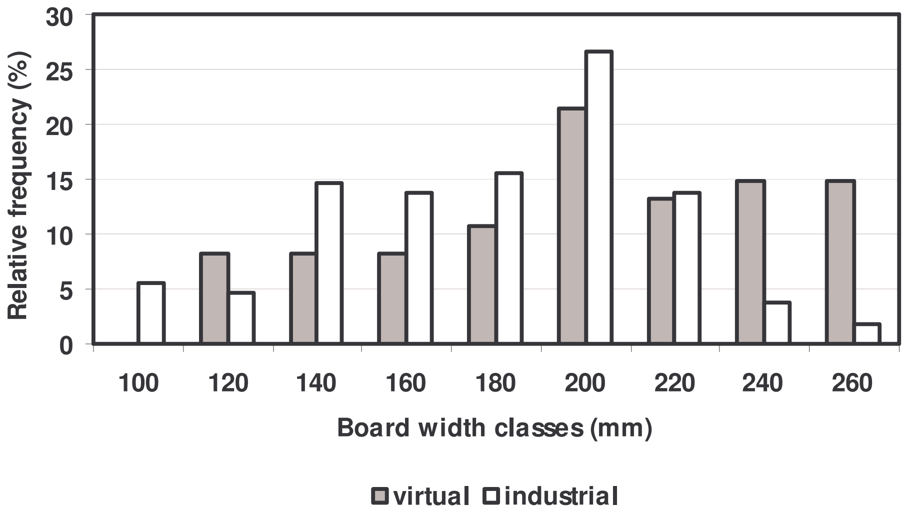

Figure 7: Distribution of board width obtained in the industrial and in the simulated sawing. Classes' 20 mm wide, central value displayed in *x* axe.

3.2 Mixed sawing pattern: lumber and boards

The sawing simulation for production of lumber and boards showed a yield 8% above the industrial yield (Table 2). When the simulation was done with all butt and top diameter matching logs from the virtual log pool, totalling 40 logs, the batch yield was 53% and individual log yield ranged from 40 to 65%.

The output for the sawing of the 3 logs batch show that the sawn products included 64% of the total volume as lumber products in the sawing simulation and 48% in the industrial sawing. More and larger lumber pieces were obtained in the virtual simulation: 9 pieces (0.13 m^3) and 7 pieces (0.08 m^3), respectively for simulation and industrial output. The number and volume of sawn boards was similar in both cases: 9 boards with 0.08 m^3 in the industrial test and 8 boards with 0.07 m^3 in the virtual sawing.

3.3 Effect of resin tapping in sawing yields

It was possible to analyse the effect of resin tapping on the sawing yields (Table 2) by comparing the yields obtained in the industrial sawing of resin tapped logs with the yields obtained by simulation of the sawing of a similar sample of logs (as the control, resin untapped logs). There was a difference with the industrial yields of the resin tapped logs lower by 11% in relation to the simulated control.

The differences between the yields of resin tapped logs and of the virtual equivalents increased with log size (Figure 8). For the smaller logs (top diameters 220-230 mm) the yields were similar and resin tapping did not seem to decrease the industrial yield. For the larger logs the loss in production yield due to resin tapping could go up to 18%.

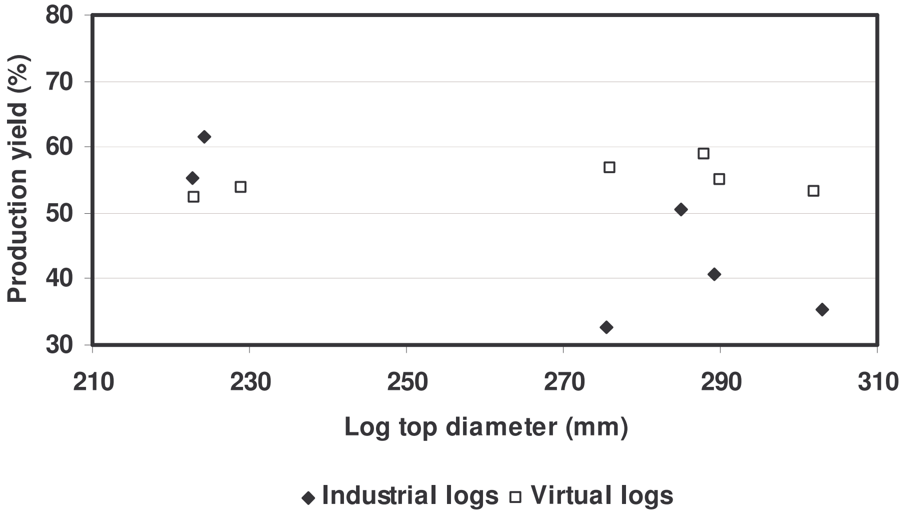

Figure 8: Yields obtained in the industrial sawing of resin tapped logs and in the sawing simulation of corresponding virtual logs

3 DISCUSSION

The results obtained with the sawing simulation of virtual logs showed the same yields as those obtained with the industrial sawing of a comparable match of logs for the production of boards (57%) and a higher yield for the production of lumber pieces and boards (45% vs. 53%) (Table 2). Overall the yield obtained with the mixed sawing pattern for lumber and boards was under the yield obtained with the single sawing pattern. The same influence of the sawing pattern on yields was reported by Richards (1973) who simulated the sawing of logs (as truncated cones) using different sawing patterns and found that the mixed sawing pattern resulted into lower yields.

However some considerations must be made in relation to the accuracy of the results. One obvious concern is the dimensioning of the sample, e.g. the number of logs, to estimate the batch yield, since individual logs show a large variation of sawing yields both in reality as in the sawing simulation of virtual logs (Table 2). The variation of batch yield with the number of logs (Figure 6) showed that for a small number of logs, the yields were highly variable but rather stabilized for samples containing more than 10 logs. The behaviour of industrial results and simulation outputs was found very similar for samples sizes of 6 or more logs.

The results regarding the production of boards, where 20 logs were tested, seem therefore to be robust. A calculation using all the virtual logs in the pool that matched the industrially sawn logs, totalling 89 logs, showed a very similar batch yield (54% vs. 57%) and range of variation for individual logs. Usenius (1980) found a difference of 0.3% by comparing industrial and simulated sawing yields concerning 25 mm thick sideboards received in the cant sawing for sawn volume corresponding to a one year production at a Finnish sawmill.
Maritime pine is a very resinous conifer and resin tapping was done extensively in Portugal, by wounding the lower part of the stem and stimulating the exudation of resin with acid. The butt log of resin tapped pines shows therefore scars on the external part of the stem. Although resin production is decreasing in Portugal for economic reasons (i.e. labour costs) many of the pine trees available for the industry have been tapped and are a concern for the sawmill. It is generally accepted that sawing yields will be lower in the case of resin tapped logs but calculations of the potential yield loss caused by resin production have not been made.
In the industrial test six of the 29 trees were resin tapped. By comparing the sawing yields of these logs with the simulation done on their virtual matched logs, it was possible to estimate the impact of resin tapping as a loss of 11% on the sawing yields (44% vs. 55%, Table 2). This loss was higher in the larger logs as these normally suffer the more severe tapping. The stem area affected by the resin tapping is in most of the logs outside the knot core zone, and although this issue was not explored here, one should expect a even higher value yield loss as this waste zone corresponds to the best board grades.
The comparison between industrial and virtual environments should also be analysed in view of the factors that can influence sawing yields. One aspect of variation is the fact that the logs used for both situations were not the same even if the sample selected as input for the sawing simulation from the virtual logs pool was carefully chosen to match as much as possible the industrially tested logs (Figure 4).
The calculation of log volume also influences on the sawing yield. The volume calculated for the virtual logs was more accurate than for the industrial logs since it was based on the sum of volumes calculated every 50 mm along the log length, while in the sawmill it was based only in butt and top diameters
In an industrial environment the factors influencing the production yield are various and random between the sawing of two logs with human operational decisions, errors along the sawing line and in measuring that affect the sawing yields. These facts are not taken into account in the sawing simulations where the calculation procedures are exactly the same for all the logs. Also, though the virtual logs used as raw material for the sawing simulation had proven to be close representations of the real ones (Pinto et al., 2003, 2004) they still were models less complex than the reality. Therefore, the dispersion of the sawing yields for the industrial logs was much higher than for the simulated ones, as there are more random effects for each log in the first case (Figure 5).
Moreover, in the industrial environment, the sawyer optimises easier the sawing for smaller logs than for larger ones while for the simulation program this is not an issue. For the larger logs higher yields were obtained in the simulation compared with the similar diameter range of the industrial sawing (Figure 5). The fact that the highest frequency of board width is between widths of 190 and 210mm in both industrial and virtual sawing showed that the majority of the logs were sawn in a similar way.
However in the industrial sawing the log was rotated by the sawyer to the best position while the simulation programme always sawed the log in the same position. Previous studies in sawing simulation of Scots pine (*Pinus sylvestris* L.) have shown that differences in yield between the worst and the best rotation angle were in average 6%, decreasing with log top diameter (Usenius et al. 1989).

The WoodCIM® virtual sawing module is able to account with other factors such as the quality of the sawing products *i.e.* knots. These features were not measured in the industrial test and therefore value optimisation could not be carried out here but the potentialities of the sawing simulation module of WoodCIM® to study the conversion chain for maritime pine were explored in Pinto et al (2002). The software allowed the new adaptations to this species and was flexible concerning the input of products and process requirements.

In resume, though further studies will be necessary to further validation, the sawing simulation module was able to reproduce the industrial sawing of maritime pine logs. The pool of 35 virtual maritime pine stems could generate a good quantity of logs with dimensions in the range of the industrial raw-material supply (129 out of 218). The stem/log mathematical reconstruction and the sawing simulation modules were useful tools to develop various sawing studies for this species, to evaluate the impact of raw material and process characteristics on the production performance, and to support the development of tools for industrial application.

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