J Wood Sci (2016) 62:400–406
DOI 10.1007/s10086-016-1566-3

ORIGINAL ARTICLE

Handling positioning errors when optimizing sawing of Scots pine and Norway spruce logs using CT scanning

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Received: 19 April 2016 / Accepted: 25 May 2016 / Published online: 7 June 2016

Abstract Since computed tomography (CT) X-ray scanning is becoming a reality in sawmills, different studies have been made to establish how well the sawing position of a log can be optimized using CT data. It is also known that positioning errors have an adverse effect on optimization, since the optimization methods used are rather sensitive to positioning errors. To mitigate the effect of positioning errors, a method is proposed in this article that filters results produced by sawing simulation, using a Gaussian filter of a size according to the positioning error. Using these filtered values for optimization, it is possible to retain two percent extra value of the sawn timber, when rotation and offset errors are present, compared to a regular optimization method. A method more robust to positioning errors is more useful in practice, since positioning errors of various magnitudes are always present in sawmills. The main contribution of this paper is, therefore, an optimization method that reduces the effect of positioning errors.

Keywords CT scanning · Sawmilling · Optimization · Positioning

Introduction

High-speed computed tomography (CT) scanning as a technology for applications in the wood industry has been realized rather recently [1]. CT scanning of wood has been used extensively in research rather than sawmill applications so far, even if some proposals for a technical solution have been presented [2, 3]. Therefore, it is of interest to propose and investigate different ways of using CT data to control the processes in the wood industry. Studies have shown that CT data can be used to control log positioning in the sawing process and improve yield and value [4–8]. In Rinnhofer et al. [4], a semi-automatic optimization using CT scanning was tested on spruce and larch, indicating a possible yield increase of 6–9 % for spruce, but zero for larch. Lundahl and Grönlund [5] varied rotation, offset, and skew of Scots pine (*Pinus sylvestris* L.) log models derived from CT scanning, then choosing the optimal position for volume yield. This increased volume yield by 4.5 % compared to sawing logs horns down and centered. In Berglund et al. [6], it is shown that choosing an optimal rotational position of Scots pine and Norway spruce [*Picea abies* (L.) H. Karst.] logs based on CT data can improve value yield by about 13 %. Van Zyl (determining the optimal log position during primary breakdown using internal wood scanning techniques and meta-heuristic algorithms, MSc thesis, University of Stellenbosch, South Africa, 2011) describes methods for faster optimization when considering internal characteristics of *Pinus radiata* (D. Don) logs. The author could increase value by 6.43 % while keeping the amount of iterations down to 200 per log. Fredriksson [7] showed that by alternating both rotation, offset, and skew of a CT scanned log, it is possible to find an optimal position leading to a value increase of 13 % compared to sawing the logs based on outer shape data alone. Finally, CT scanning together with computer simulation models can be used to control a process involving several production units, thus avoiding sub-optimization. This leads to increased recovery in the entire chain of production [8].

However, the methods used in those studies did not account for possible errors in positioning the logs during

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sawing. In, for instance, Berglund et al. [6], Todoroki [9], Wessels [10], and Tulokas and Tannous [11], it is shown that a positioning error when optimizing log position during sawing can have detrimental effects on the possibility to find an optimal solution. In other words, the methods used are sensitive to positioning errors. The value potential can be severely reduced by the presence of variation in the sawing position, something which is very much a reality in sawmills, and, therefore, needs to be taken into consideration if a favorable sawing position is to be achieved. The causes for positioning errors can be several, for instance, log movement on the conveyor, log scanning errors, errors in the control software, or the rotation mechanism itself [12].

The objective of this study was, therefore, to develop and analyze a robust method for finding an optimal sawing position of a log, taking into account possible positioning errors. The idea behind this is that if the size of positioning errors is known, computer simulations can be done to predict the sawn timber value at different positions creating a multi-dimensional value plot, which can be filtered in an appropriate way to account for the positioning errors. From this filtered surface, an optimal position of logs can be chosen, with positioning errors in mind. As a second objective, this robust method was to be compared to two other ways of positioning logs: Horns down and centered, and a naive optimization strategy not accounting for positioning errors. 'Horns down' means that the logs is rotated, so that the main sweep is facing upwards [13], Fig. 1.

The main contribution from this paper is that positioning errors are taken into account when optimizing sawing position, something which was not done in the studies discussed in the introduction.

Materials and methods

The stem bank

This study was based on the Scots pine (*Pinus sylvestris* L.) and Norway spruce [*Picea abies* (L.) H. Karst.] logs of the Swedish Pine Stem Bank [14] and the European Spruce Stem Bank [15]. The stem bank trees, from well-documented sites at different locations in Europe, have been documented thoroughly regarding both tree properties and silvicultural treatments. They were scanned with a medical CT scanner (Siemens SOMATOM AR.T) to record internal properties, such as knots. Knots in the stem banks are described by a parameterized model, which takes into account curvature of the knot and diameter in two log directions, tangential and longitudinal. Each knot is divided into a living part and a dead part. Details on the log and knot models are given by Grönlund et al. [14] and Nordmark [16].

To supplement the stem banks with material collected more recently, 10 Scots pine and 10 Norway spruce logs were collected at the log yard of a sawmill in northern Sweden, at around lat. 64°, close to the coast of the Baltic sea. The origin of these logs was not known at the same detailed level as for the stem bank logs, since they were taken from a log yard. Table 1 shows the range of some of the most important log features for the 20 extra logs.

The logs were transported around 10 km, and scanned using a medical CT scanner (Siemens SOMATOM AR.T). The whole procedure took around 10 days, during which the logs were stored outside in a temperature that varied between −7 and 11 °C. A small amount of drying of the sapwood could be observed, but no complete drying of the logs took place.

The number of logs in the Swedish Pine Stem Bank was 715, and the number of logs in the European Spruce Stem Bank was 750. This means that the total number of logs in this study was 1485; 725 Scots pine logs and 760 Norway spruce logs.

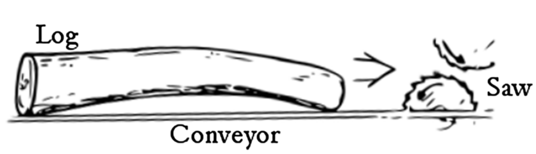

Fig. 1 Illustration of sawlog being sawn 'horns down'

Sawing simulation software

Sawing simulation was performed using the simulation software Saw2003, developed by Nordmark [16]. The input was log models, based on the CT scanned logs. The log models were constructed by the parameterized knot models and the outer shape of the log. For the logs scanned specifically for this study, a knot detection method developed by Johansson et al. [17] was used.

Table 1 Summary of data for the extra logs that were scanned and used together with the stem banks in this study

Species Log feature	Scots pine		Norway spruce	
	Minimum	Maximum	Minimum	Maximum
Top dia. (mm)	148	227	143	232
Length (m)	3.4	4.9	3.1	5.1
Volume (m^3)	0.069	0.20	0.074	0.21
Taper (mm/m)	2.9	12	4.9	21
Bow height (mm)	4	20	5	23

Top dia. log top diameter measured 10 cm from the top end

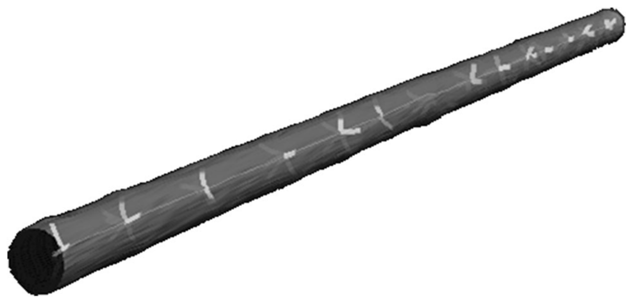

Fig. 2 Example of log model used in this study

Saw2003 models a sawmill that employs cant sawing with two sawing machines, with curve sawing in the second saw, edging and trimming. The latter two are value-optimized according to timber prices and grading criteria. It is also possible to control positioning of the logs during sawing.

Grading of the sawn boards in Saw2003 is done according to the Nordic Timber Grading Rules [18]. Boards are graded into three quality classes, A, B, or C, where A is the class with the strictest requirements. The grading is based on knots and wane only, since other board features, such as pitch pockets or rot, are not represented in the stem bank. An example of a log model used in Saw2003 is shown in Fig. 2, with outer shape and knots.

The sawing simulation results in virtual boards with information about knots, dimensions, quality, value, and so forth. Saw2003 has been used extensively in earlier research [5–8, 16, 19, 20].

Settings used for simulations

The sawing pattern for each log was chosen according to the top diameter, a manner typical of Scandinavian sawmills. The corresponding sawing patterns for different top diameters are presented in Table 2. Since Saw2003 employs value-optimized edging and trimming, the price relation between different board qualities affects the simulation result. This is, for instance, shown in Berglund et al. [6]. The prices of sawn timber used in this study were 185, 160, and 100 €/m^3, for center boards of A, B, and C quality, respectively. For the sideboards, the prices were 300, 140, and 110 €/m^3, also for A, B, and C quality. Sideboards were edged to widths of 75, 100, 115, 125, 127, 150, 175, 200, or 225 mm, with a fixed thickness of 19 or 25 mm depending on the position in the sawing pattern. All boards were trimmed to module lengths of $1800 + n \times 300$ mm modules, $n = 1, 2\ldots$ The logs were curve sawn, so in the second saw, the saw kerf followed a second degree function that was fitted to the centerline of the cant.

Table 2 List of sawing patterns used in this study

Lower diameter limit (mm)	Upper diameter limit (mm)	No. of centerboards	Width (mm)	Thickness (mm)
0	129	2	75	38
130	149	2	100	38
150	169	2	100	50
170	184	2	125	50
185	194	2	125	63
195	209	2	150	50
210	219	2	150	63
220	229	2	175	50
230	249	2	175	63
250	264	2	200	63
265	284	2	200	75
285	304	2	225	75
305	324	4	200	50
325	344	4	225	50
345	384	4	200	63
385	449	4	200	75

Lower diameter limit = smallest top diameter allowed for logs within this sawing pattern. Upper diameter limit = largest top diameter allowed for sawing pattern. Width = nominal width of centerboards (main yield). Thickness = nominal thickness of centerboards. Sideboards were edged to various sizes depending on value

Log positioning

Two types of log positioning were investigated in this study; these are presented in Fig. 3. When a log was rotated, it was turned around its central axis. Offset of a log meant that it was moved in a lateral direction, but not turned in any way.

Using Saw2003, each log was sawn in 36 different rotational directions, in 5° intervals starting at the position in which the log was scanned. This means that one half turn was achieved, but since the sawing patterns used were symmetrical, a second half turn was not needed. For each rotational position, five different offsets were tested: fully centered, 3.5 mm to the left and right, and 7.0 mm to the left and right. This means that each log was sawn in 180 different positions. The number of positions was chosen as a compromise between resolution and computational time, and the interval of offset corresponds to results from the previous research on similar material, e.g., Fredriksson [7].

Data analysis and filtering

The value of the sawn timber for each position was stored, thus creating a value surface for each log, which is a

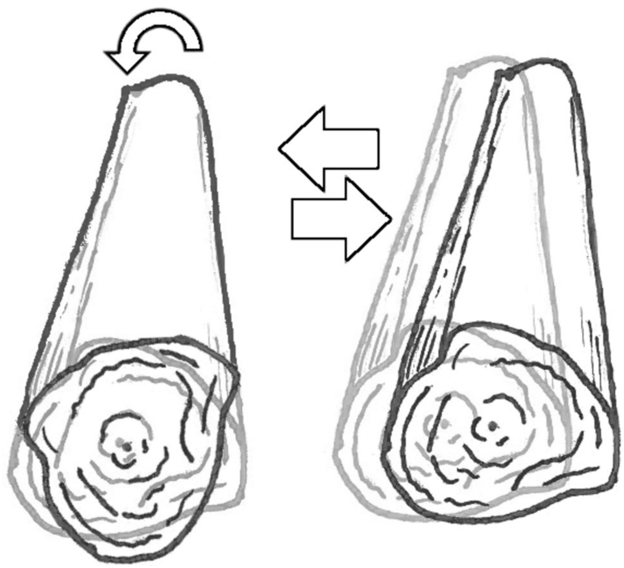

Fig. 3 Two types of positioning displacement studied, from *left* to *right*: rotation and offset

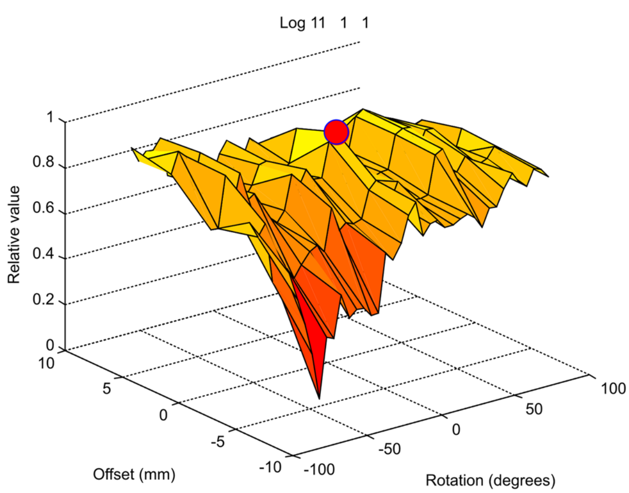

Fig. 4 Example of a value surface, showing *values* of sawn timber depending on rotational position and offset of one log. The value is normalized, so that the maximum value corresponds to 1, and all other values are calculated as a share of the maximum. Zero rotation corresponds to the 'horns down' position. The *circle* indicates the maximum value, in this case a position close to the horns down and centered position. "Log 11 1 1" refers to the log number used, which is log 1 from tree 1 in plot 11 of the Swedish Pine Stem Bank [14]

surface plot with sawn timber value on the z-axis, offset on the x-axis, and rotation on the y-axis (see Fig. 4).

The value surface of each log was filtered using a two-dimensional Gaussian filter, with a standard deviation corresponding to that of the positioning error. The size of the filter kernel was, therefore, different in different directions, with the corresponding standard deviation being used in the rotational direction and the offset direction,

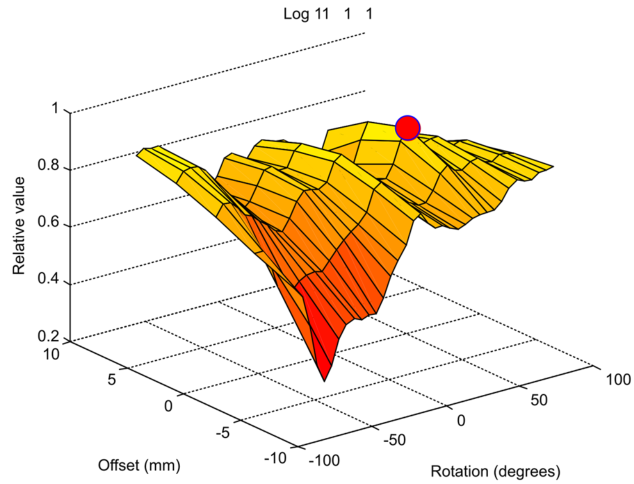

Fig. 5 Example of a filtered value surface, showing values of sawn timber depending on rotational position and offset of one log. In this case, a filter kernel was used with a standard deviation of 5° in the rotation direction and 3.5 mm in the offset direction. Zero rotation corresponds to the 'horns down' position. The *circle* indicates the maximum value position. Note that this position is different from that of Fig. 4, indicating a position less sensitive to positioning errors. "Log 11 1 1" refers to the log number used, which is log 1 from tree 1 in plot 11 of the Swedish Pine Stem Bank [14]

respectively. Using a Gaussian filter assumes that the positioning error is normally distributed, which is reasonable if it can be considered as a random error, according to the central limit theorem. A filtered value surface is shown in Fig. 5, using the same log as in Fig. 4.

Before filtering, the boundaries of the value surface were padded. In the rotational direction, padding was done simply by adding data columns from the opposite boundary, but mirrored in the offset direction. This is possible, since the sawing patterns used were symmetrical, so in the rotational direction, the value surface is periodical with a period of 180°, however, mirrored in the offset direction, since the left side of the log becomes the right side and vice versa. In the offset direction, tests were made using both a duplicate of the boundary value as well as using zero values as padding. However, both these assumptions are far from the real situation, as shown in Todoroki [9]. The value rather follows a function proportional to $1/x$, where x is the distance from the center. Therefore, the padding in the offset direction was made using Eq. 1.

$$z(x, y) = \frac{2 \times z_{b(y)}}{x + 1} \tag{1}$$

where $z =$ the value to be used for padding at position x from the boundary at rotational position y, and z_b is the value at the boundary at rotational position y. Thus, the padding value closest to the edge ($x = 1$) is a duplicate of the edge value, and all others are proportional to $1/x$. The

Table 3 Levels of the standard deviations used for different error sizes

Scenario	Rotation standard deviation (°)	Offset standard deviation (mm)
Low level	5	3.5
Medium level	10	7.0
High level	15	10.5
Only rotation	10	0.0
Only offset	0	7.0
No error	0	0.0

reason for not choosing a simpler function, such as $1/x$, was that it resulted in a very steep value decrease compared to the previous research done by Todoroki [9] and also turned out to work less well when tested.

Testing the method

The optimal positions obtained using filtering of the value surfaces were used for sawing simulation, where positioning errors were added. Each log was sawn in the highest value position, with a normally distributed error of both rotation and offset added. The error distribution was symmetrical and centered on 0. Five different levels of errors were tested, as described in Table 3. The levels were chosen as a high, medium, and low level of both types of errors combined, i.e., in the rotation and offset direction. In addition, two scenarios, including only rotational errors and only offset errors, were tested. Subsequently, the value surface of each log was filtered in a different way for each scenario, using the corresponding standard deviations. The ranges were chosen in accordance with industry studies made by Sederholm [21, 22], Vuorilehto and Tulokas [12], and Øvrum [23]. In these studies, offset standard deviations in the first saw were usually between 5 and 10 mm, and in severe cases a bit over 10 mm. Rotation error standard deviations ranged from 8° to 15°. Finally, a scenario without any positioning error was tested.

Sawing simulation was also done with two reference sawing positions, one where the log was sawn horns down and centered, and one where the log was sawn in the position giving the highest value of sawn timber without any positioning errors, i.e., a naive optimization strategy choosing simply the highest value, such as in Fig. 4. The same positioning errors as described in Table 3 were added to these choices of position as well.

For all tests, the randomization algorithm was seeded using the same seed each time, to enable comparison between the different positioning choices, i.e., using common random numbers [24].

Results

The value of the sawn timber from each scenario, using different ways of positioning the logs, is presented in Table 4.

The robust position performed better than the naive position for all error levels, increasing the potential value gain by 1.6–2.4 % points, compared to sawing logs horns down and centered. The pure rotation error has a more severe effect on value than a pure offset error, for the error size used.

Figure 6 shows how often the naive and the robust sawing position coincided, for the different positioning error levels and for all logs. The larger the error, the less frequently the two positions were the same.

Discussion

Positioning errors affected the value of the sawn timber in this study, regardless of whether the logs were sawn horns down and centered, or with one of the two positioning

Table 4 Value of the sawn timber for different levels of positioning errors and different choices of sawing position

Positioning Error scenario	Centered, horns down	Naive position		Robust position	
	Value (€)	Value (€)	% increase	Value (€)	% increase
Low level	21,441	22,951	7.0	23,304	8.7
Medium level	20,388	21,179	3.9	21,669	6.3
High level	18,996	19,483	2.6	19,893	4.7
Only rotation	21,766	23,170	6.5	23,510	8.0
Only offset	20,367	22,176	8.9	22,515	11
No error	21,771	25,469	17	N/A	N/A

When no error is present, the naive position and the robust position coincide

N/A not applicable

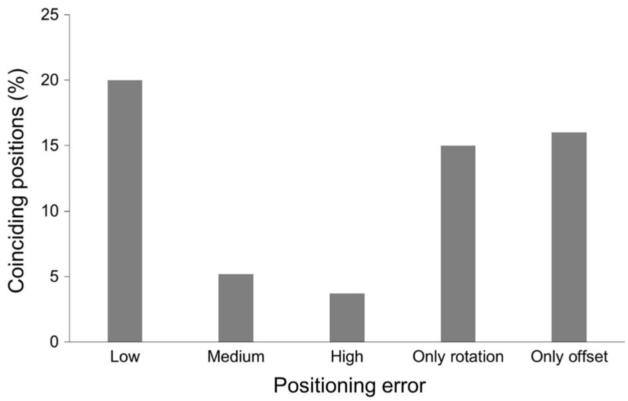

Fig. 6 Share of coinciding positions for all 1485 logs of this study, between the robust and the naive option of choosing sawing position. The positioning error levels are the same as those described in Table 3

optimization methods based on CT scanning. A larger error level meant a lower value of the sawn timber. However, when the robust method was employed, this reduction was less significant. Instead of using a naive method of just choosing an ideal maximum, i.e., when no positioning errors are assumed, the robust method can be used to gain more value from logs using CT data. The difference was around two percentage points of value yield in this study.

The robust method performed better than the naive method regardless of the size of positioning errors, and the difference between the two is rather consistent. Furthermore, for relatively large positioning errors, the naive method only increases value yield by 2.6 %, meaning that the benefit of using CT data for positioning is almost eradicated. This shows the importance of reducing variation in the sawing process, especially when advanced scanning equipment is being used to control the process.

When positioning errors were small, the naive method and the robust method chose the same sawing positions to a larger extent than when errors were larger. This is intuitive, since for a large positioning error, the robust method chose low risk areas of the value surfaces, while if the error was small, it chose more high risk peaks. The naive method always used the absolute maximum value, meaning that such peaks were frequently chosen regardless of how large the positioning error was.

Both methods managed to increase the value of the sawn timber compared to sawing logs horns down and centered. The latter method is not always used in sawmills; however, it works as a good reference point, since it is rather independent of prices, qualities, and other factors affecting optimization.

In a practical situation, there are other factors affecting the possibilities for optimization. For instance, in this study, it was assumed that the positions of knots were fully known, something which is not true in practice. Although knot detection algorithms are working rather well, they are not perfect. The detection rate of knots is between 88 and 94 %, and the root mean square error for knot size is around 5 mm [17].

The robust method used in this study also assumed that the distributions of positioning errors are fully known. This is never true in a practical situation; however, if the sawmill works actively with measurements and follow up of the positioning of the sawing machines, the error distribution can be relatively well predicted. Furthermore, it was assumed that the error distribution is normal, symmetrical, and centered on 0. This is probably not always the case either, as shown in Vuorilehto and Tulokas [12], but there is no reason to believe the method would not work for other types of distributions as well, as long as they can be estimated. In addition, a sawmill working with quality control should ensure that the positioning errors they have, are indeed 0 in average. They would also want to remove any non-random errors, thus the remaining errors should be normally distributed according to the central limit theorem. All in all, the assumed error distribution can still be considered as a limitation of this study.

One final limitation of this study is that it was based on Scandinavian industrial praxis, in terms of sorting logs, of sawing, and of grading the sawn timber. In this study, the logs were not graded, only sorted according to top diameter and sawn in different ways according to the sorting. This may affect the results. In addition, only rotation and centering in the first saw was tested. If skewing and positioning errors in the second saw were added, it would add to the complexity of the method, but it would also account for the real situation in a sawmill to a larger extent. This was not included in the scope of this study for the sake of brevity; however, it could be a subject for future studies.

Since the study was made using simulations, it is not certain that the sawn timber will look exactly the same in a practical situation. However, since three cases were compared within the same simulation environment, with the same conditions except for the method used, the comparison between the different methods is valid.

To summarize, it can be concluded that a sawing positioning method based on CT scanning that takes positioning errors into account can mitigate the effect of these errors to a large extent. Compared to a more naive method of choosing the ‘best’ position regardless of errors, it improves value yield by around two percent, depending on the size of the positioning error. Compared to sawing logs horns down and centered, it improves value yield of 4–11 %, also depending on the positioning error size. The method is robust to errors of a rather large size, in the higher range of the measurements that has been done in the previous research. No extra hardware is required compared to the naive method, what is needed though is active work by sawmills to measure and follow up on the size and distribution of positioning errors. This build upon previous work by not only assessing the possible value gain by optimizing log sawing position, but also taking into consideration the positioning error.

Acknowledgments The author would like to thank the ÅForsk Foundation together with the Sweden-America Foundation and Stiftelsen Tornspiran for lending financial support for this study. Also, I would like to thank Dr. Erik Johansson at SP Technical Research Institute of Sweden, together with Birger Marklund at Luleå University of Technology, for assistance with scanning of logs and creation of log models for simulation.

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